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Fly-by-Light Flight Control System Technology Development Plan Final Report

A. Chakravarty, J. W. Berwick, D. M. Griffith,
S. E. Marston, and R. L. Norton

Boeing Commercial Airplanes
P. O. Box 3707
Seattle, Washington 98124-2207

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Langley Research Center
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CONTENTS

FIGURES

GLOSSARY

A429	ARINC 429 data bus
A568	ARINC 568 data bus
ACARS	ARINC communications addressing and reporting system
ACE	actuator control electronics
ADIRU	air data inertial reference unit
ADIRS	air data inertial reference system
AOA	angle of attack
AI	artificial intelligence
APB	auxiliary power breaker
APU	auxiliary power unit
ARINC	Aeronautical Radio, Inc.
ARP	avionics research pallet
ATC	air traffic control
ATOPS	advanced transport operating system
BTB	bus tie breaker
C	center
CDR	critical design review
CDU	control display unit
CMP	control and mode panel
CPU	central processing unit
DAS	data acquisition system
DATAC	digital autonomous terminal access communications
DHC	display host computer
DHU	display host electronics unit
DMA	direct memory access
DU	display unit
EASILY	Experimental Avionics Simulation and Integration Laboratory
EE	electronic equipment
EEC	electronic engine control
EICAS	engine indication and crew alerting system
EIU	effector interface unit
EMI	electromagnetic induction
EMP	electromotor pump
EPC	external power contractor
EXP P	experimenter's pallet
FBL	fly-by-light
FBW	fly-by-wire

FLTCNT	flight controls
FLTMGT	flight management
FO	fiber-optic
FY	fiscal year
GCB	generator circuit breaker
GPS	global positioning system
HERF	high-energy radio frequency
H/W	hardware
IACS	integrated avionics computer system
IAU	interface adapter unit
ILS	instrument landing system
IPL	interprocessor link
L	left
LaRC	Langley Research Center
LDR	loader
LED	light-emitting diode
LRRA	low-range radio altimeter
LRU	line replaceable unit
MIL-C	military connector
MIU	maintenance interface unit
MLS	microwave landing system
NASA	National Aeronautics and Space Administration
OD	on dock
PADS	piloted aircraft data system
PCE	pilot control electronics
PDR	preliminary design review
PDU	power drive unit
PFC	primary flight computer
PFD	processed flight data
PMG	permanent magnet generator
PS	power supply
PSA	power supply assembly
P_S	static pressure
P_T	total pressure
R	right
RAT	ram air turbine
RFD	research flight deck
RFDIP	research flight deck interface pallet

RS232	RS232 data bus
SAARU	standby attitude and air data reference unit
SAC	side arm controller
SFC	secondary flight computer
SIP	sensor interface pallet
SIU	sensor interface unit
SOW	statement of work
SU	sensor unit
S/W	software
TAT	total air temperature
TCM	technical coordination meeting
TDS	thermal detection system
TLA	throttle lever angle
TNC	terminal node controller
TRU	transformer rectifier unit
TSRV	Transport Systems Research Vehicle
VIU	VME bus interface unit
VLSI	very large scale integration
WDM	wavelength division multiplexing

1.0 SUMMARY

This report documents the results of a four-month effort to develop a Fly-by-Light (FBL) Technology Development Plan. The study investigated the possible application of fiber-optic FBL components in phases. The production configuration was defined for a 757-type airplane. For each phased application of fiber-optic components, the technical shortfalls were identified and a development plan to bridge the technical gap under NASA leadership was developed.

Even though the production configuration is defined for a 757, it is recommended that the demonstration flight be conducted on the NASA Transport Systems Research Vehicle (TSRV), a Boeing 737. The modifications necessary to the NASA TSRV have been delineated, as have the significant certification issues relative to verification and validation.

Finally, a detailed schedule for the phased introduction of FBL system components has been generated. Flight testing on the NASA TSRV will start in September, 1992 and continue through December, 1995.

It is concluded that even though fiber optics, being a developing technology, suffers in terms of cost estimates, a viable fiber-optics program would contribute significantly towards developing the required state of readiness that will make a FBL flight control system not only cost effective (vendors will lower their price quotations after successful demonstration) but also reliable, without mitigating the weight and high-energy radio frequency (HERF) related benefits. The weight benefits should actually improve with a successful development and demonstration.

2.0 INTRODUCTION

NASA has solicited from aircraft manufacturers recommendations for a Fly-by-Light (FBL) Technology Development Plan to develop, implement, and test an FBL flight control system that could be made available for revenue passenger introduction by the year 2000. The development of this FBL flight control system will require a significant financial investment. It is therefore necessary to determine the areas of greatest potential benefit and a viable plan to develop the required technology.

Recent insistence by the regulatory agencies that avionics systems should be able to withstand more stringent high-energy radio frequency (HERF) immunity requirements has prompted a fresh look at fiber-optics for possible application outside the pressure vessel. The immunity of fiber optics to HERF and lightning and its lower weight makes it an attractive candidate for signaling, sensor application, and optohydraulic-type actuators in any flight control system.

Even though fiber-optics, being a developing technology, suffers in terms of cost estimates, a viable fiber-optics program would contribute significantly towards developing the required state of readiness that will make an FBL flight control system not only cost effective (vendors will lower their price quotations after successful demonstration) but also reliable, without mitigating the weight and HERF-related benefits. The weight benefits should actually improve with a successful development and demonstration.

2.1 OBJECTIVES

The main objective of the FBL flight control system study program was to develop a Technology Development Plan for supporting a certified, operational introduction of an FBL flight control system by the year 2000.

The specific objectives were:

a. Definition of the FBL flight control system configuration.
b. Identification of the fiber-optic shortfalls and gaps.
c. Definition of benefits in terms of life cycle cost and weight.
d. Identification of certification, verification, and validation issues.
e. Development of an FBL flight control system development plan.
f. Identification of modifications necessary to the NASA TSRV to accomplish the demonstration flight test.
g. Generation of detailed flight test demonstration schedules and resource requirements for the prime contractor and suppliers.

2.2 APPROACH

The application areas of fiber-optic technology and their phased introduction, depending on production readiness (assuming inservice evaluation, development of manufacturing processes, etc.), were determined. These findings supported a configuration definition (with the 757 as the candidate aircraft) that started with fiber-optic ARINC 629 signaling and was augmented with other fiber-optic elements (e.g., sensors and actuators) as they became available for FBL application. For each fiber-optic item (e.g., ARINC 629 signaling, sensors, and actuators), the technology gaps were identified and research and development activities required to bridge the gaps were defined in those areas appropriate for government support.

The cost and weight (proprietary data) of the FBL system with fiber-optic digital autonomous terminal access communications (DATAC) were compared to those of the 757 mechanical baseline and a previously defined 757 fly-by-wire (FBW) system. The cost and weight (proprietary data) of adding optical sensors and optohydraulic actuators were also evaluated. The unresolved certification issues relative to verification and validation were identified. The schedule of activities required to get to production readiness was laid out and the resources required from NASA to accomplish the development activities, including the Transport Systems Research Vehicle (TSRV) modification and the demonstration flight test, were defined.

2.3 SCOPE

This report contains nine sections. Section 3 describes the FBL flight control system configuration that was used for cost and weight trades, and shows the phased introduction of fiber-optic technology. Phase I starts with fiber-optic ARINC 629 signaling, phase II includes optical sensors and optical signaling to actuators with electronic amplification, and phase III further includes optohydraulic actuators with optical control power.

Section 4 describes the technical "shortfalls" and "gaps" for each fiber-optic application, while section 5 identifies the key certification issues, including issues related to verification and validation testing.

Section 6 includes the technology development plan to get to production readiness for each fiber-optic element of the FBL system and section 7 discusses the modifications required on the NASA TSRV to demonstrate in flight the preferred FBL flight control system. Finally, section 8 lays out the schedule of tasks to reach the stage of production readiness and section 9 delineates the resources required from NASA by the prime contractor and its suppliers to accomplish the needed tasks under NASA leadership.

3.0 CONFIGURATION DEFINITION

The approach to the definition of the fly-by-light (FBL) flight control system configuration began with an examination of the elements of that system to determine whether or not the fiber-optic technology for their implementation was available and, if so, with what degree of maturity. After the fiber-optic shortfalls and gaps were identified (sec. 4), the penetration of fiber optics was introduced in three phases. It was an objective to maintain safety with the FBL configuration at levels equal to or greater than current levels.

The first phase (i.e., revenue service introduction in 1997) will use fiber-optic ARINC 629 signaling and *distributed* actuator control electronics (ACE) (fig. 3-1). A *consolidated* ACE architecture (with the units in the electronic equipment (EE) bay) was also examined but not considered for phase I. The penetration of fiber-optics ARINC 629 signaling is very minimal with the consolidated architecture because all of the ARINC 629 network is inside the EE bay. The ACE-to-actuator connection is wire in a flex conduit. Phase II (i.e., revenue service introduction in 1998) will have *consolidated* ACE and use optical position sensors for loop closure, optical signaling to actuators with electronic amplification (fig. 3-2), and optical linkage from the optical throttle lever angle (TLA) resolver to the electronic engine control (EEC). The optical link at the engine requires a high-temperature/vibration harness. Phase III (which calls for revenue service introduction no earlier than the year 2000) will add optohydraulic actuators with optical control power.

The production airplane is considered identical to a 757 for the purpose of the FBL configuration definition and includes:

a. <u>Sensors</u>

ADIRS

The air data inertial reference system (ADIRS) consists of one air data inertial reference unit (ADIRU), one standby attitude and air data reference unit (SAARU), three air data modules each for total and static pressures (P_T and P_S), three angle-of-attack (AOA) modules and one total-air-temperature (TAT) module, all communicating via fiber-optic ARINC 629 buses (fig. 3-1).

For the purpose of reduced sensor complexity and high-energy radio frequency (HERF) protection, optical sensors and feedback loops will be used in phases II and III of the FBL system. Most of these sensors are expected to be available for operational introduction by 1998. The optical sensor candidates for the use of optics and their quantities per airplane are shown below:

a. All linear and rotary position sensors (43).
b. AOA sensors (3).
c. TAT sensor (1).

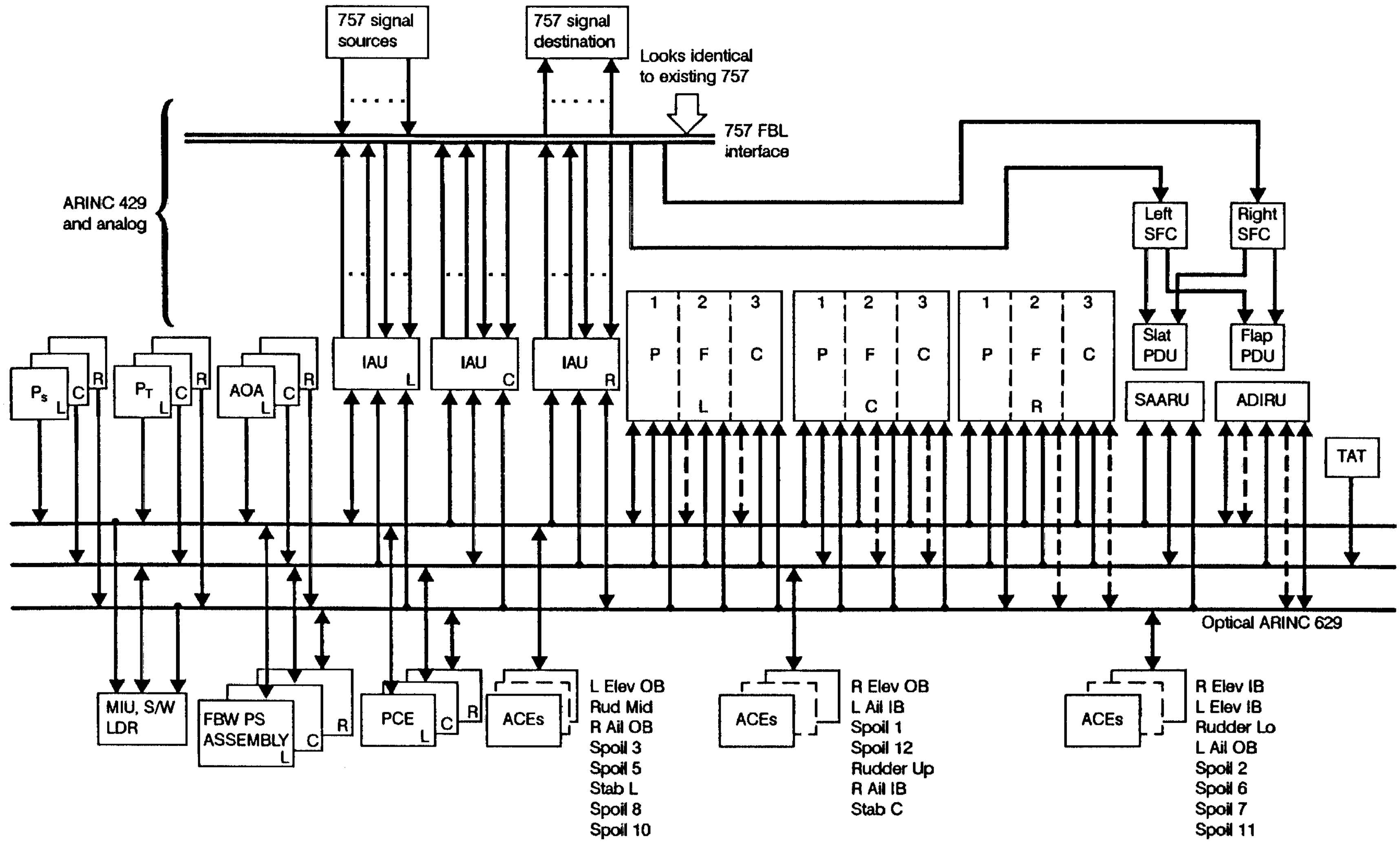

Figure 3-1. Fly-by-Light Architecture With Distributed ACEs

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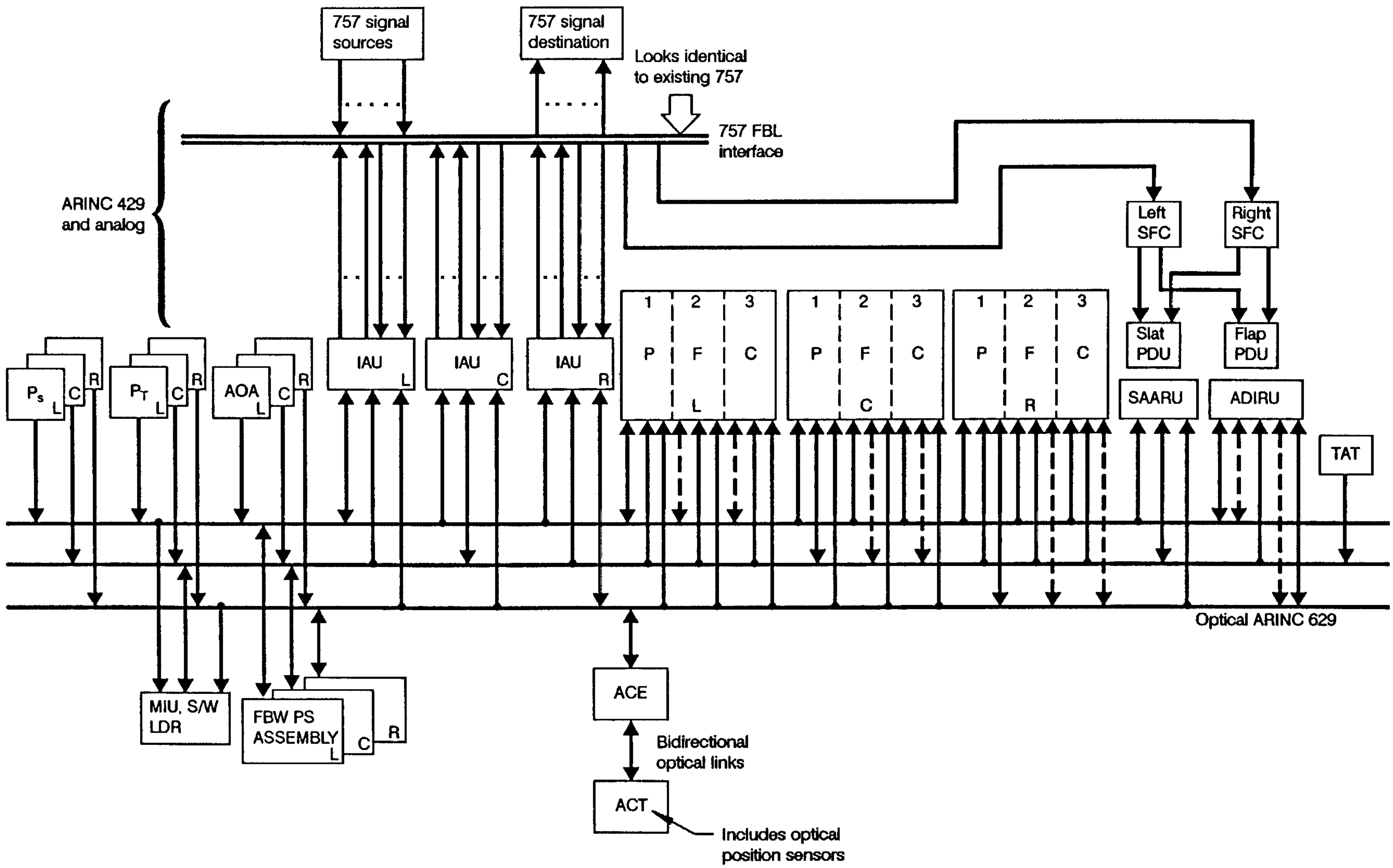

Figure 3-2. Fly-by-Light Architecture With Consolidated ACEs

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A typical optical position transducer is shown in figure 3-3. The number of fibers between the opto-electronics and the remote transducer has been reduced with wavelength division multiplexing (WDM). Broad-spectrum light from the light-emitting diode (LED) source is divided at the remote WDM into smaller wavelength bands to illuminate each track of the reflective pattern on the code plate. The reflected signals are recombined through the remote WDM and returned to the optoelectronics, where they are divided by a matching WDM to illuminate a detector array. The receiver circuit decodes the spectrum to identify the linear position sensed.

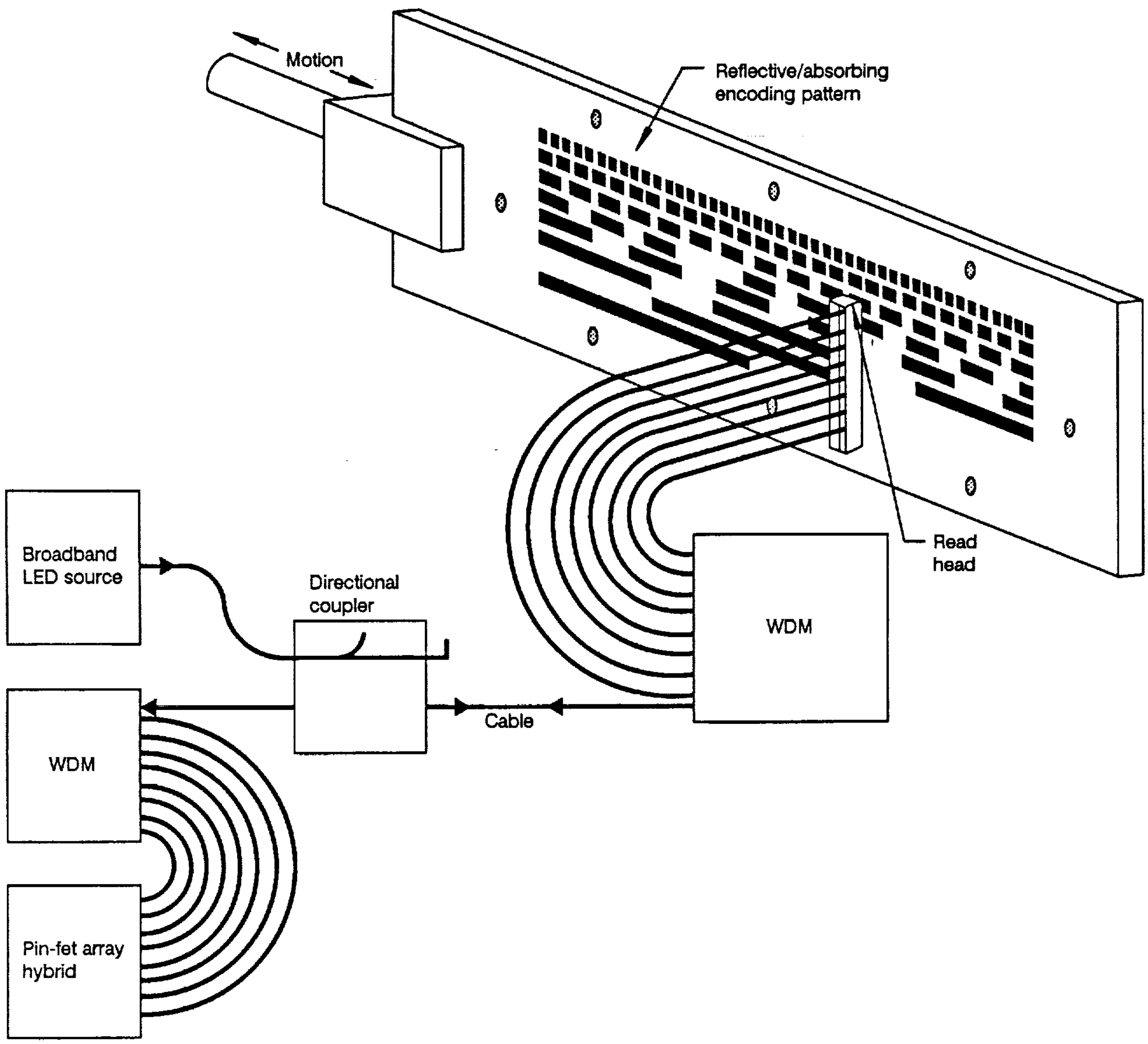

Figure 3-3. Typical Position Sensor

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The sensor described above is only an example and the technology it uses need not be optimum for our application. We will study issues relative to reliability, availability, accuracy, and so forth and choose the most appropriate technology to be applied in a particular kind of sensor. The interconnect fiber count to several transducers can also be reduced by wavelength multiplexing the signals onto a single fiber.

The TLA resolver shall be a fiber-optic rotary position sensor and the electrical wire between the TLA sensor and the EEC replaced by optical cable.

b. Controllers

The captain and first officer will use column and wheel controls for all three phases of the FBL flight control system program.

c. Primary and Secondary Flight Computers

1. Primary Flight Computer

The primary flight computers (PFC) will consist of triple dissimilar channels to ensure fault tolerance to common mode faults in those elements. Each channel will have dissimilar processor hardware and software and will include three similar hardware and software lanes.

2. Secondary Flight Computer

The secondary flight computers (SFC) are envisioned as dual boxes, with each box having dual dissimilar processors.

d. Actuators and Control Electronics

The ACE consists of distributed ACE and actuator pairs for phase I of the architecture. The ACE will be mounted 2 ft or less from the actuator. The ACE-to-actuator connection will be wire in a flex conduit. The number of independent actuators are delineated in figure 3-1. There will also be three pilot control electronics (PCE) units that will collect inputs from the captain and the first officer and distribute them to the individual PFCs and ACEs over fiber-optic ARINC 629 buses. The backup mode will use analog fiber-optic links from the PCEs directly to the ACEs. Implementing this mode involves choosing a command signaling protocol and preparing design using commercially available LEDs and photodiode amplifiers. Each analog link to the ACE will be unidirectional.

For phases II and III, the architecture will use ACEs (fig. 3-2) located in the EE bay (as opposed to distributed ACE and actuator pairs). Downstream of the year 2000, when optical computing becomes available, distributed ACEs would be the preferred implementation (fig. 3-4) for ostensible weight benefits.

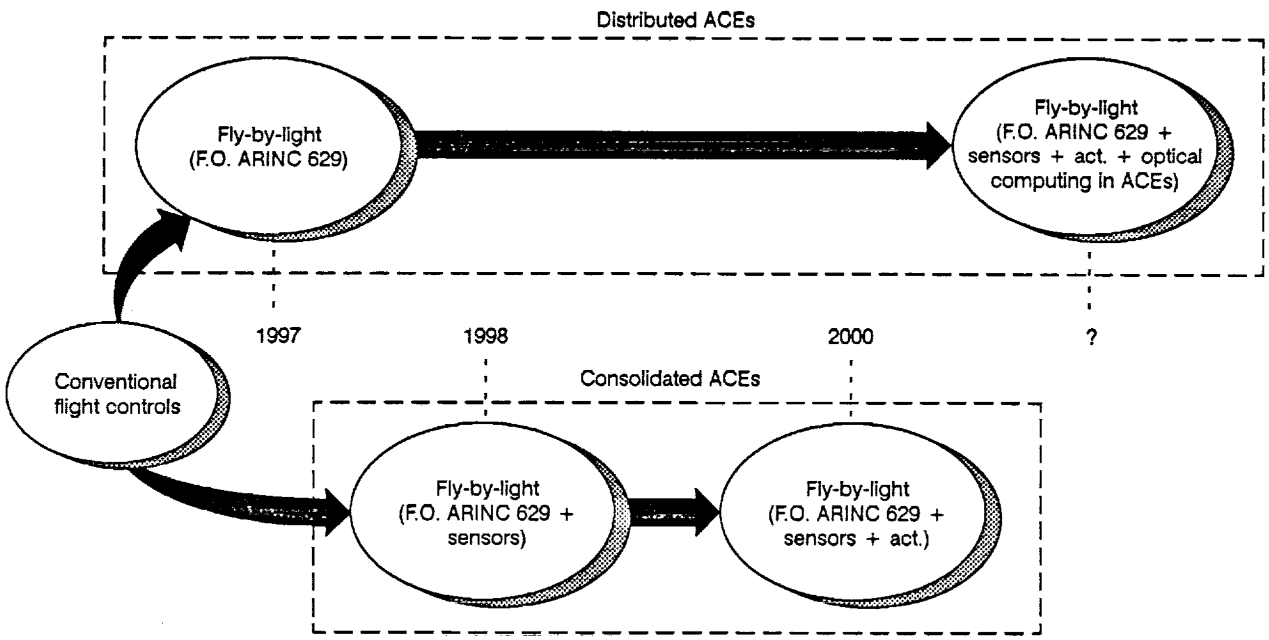

Figure 3-4. Fly-by-Light Flow Chart of Viable Architectures

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e. Electrical Power Sources and Distribution

The FBL flight control system will use triplex 28V dc buses with bus controllers; each bus will be supported by an independent 5-min battery in FBL power supply assemblies. Each bus will be connected to a permanent magnet generator on each of the two engines and the auxiliary power unit (APU). A ram air turbine (RAT) will be available to supply power to all three buses in the event of loss of engine and APU power in flight. On the ground with no engine or APU power, the FBL buses will be connected to the airplane 28V dc buses. The baseline electrical power system is shown in figure 3-5. It ensures the availability of redundant sources to supply dependable, uninterruptable FBL power for safe flight and landing.

The FBL electrical power supplies will be immune to HERF and electromagnetic interference (EMI).

f. DATAC Data Buses

There will be triplex FBL ARINC 629 data buses as shown in figures 3-1 and 3-2. These will be fiber-optic buses with two fibers in the main bus and four fibers in the stubs. The data rate will be 2 Mbps. The ACEs, PFCs, FBL power supply assemblies, ADIRU, SAARU, and the air data modules will communicate directly on the DATAC buses. Other supportive systems with ARINC 429 electrical terminals are all in the EE bay with adequate electromagnetic shielding and do not need to be converted to fiber optic. These systems shall interface with the above line replaceable units (LRU) via three interface adapter units (IAU).

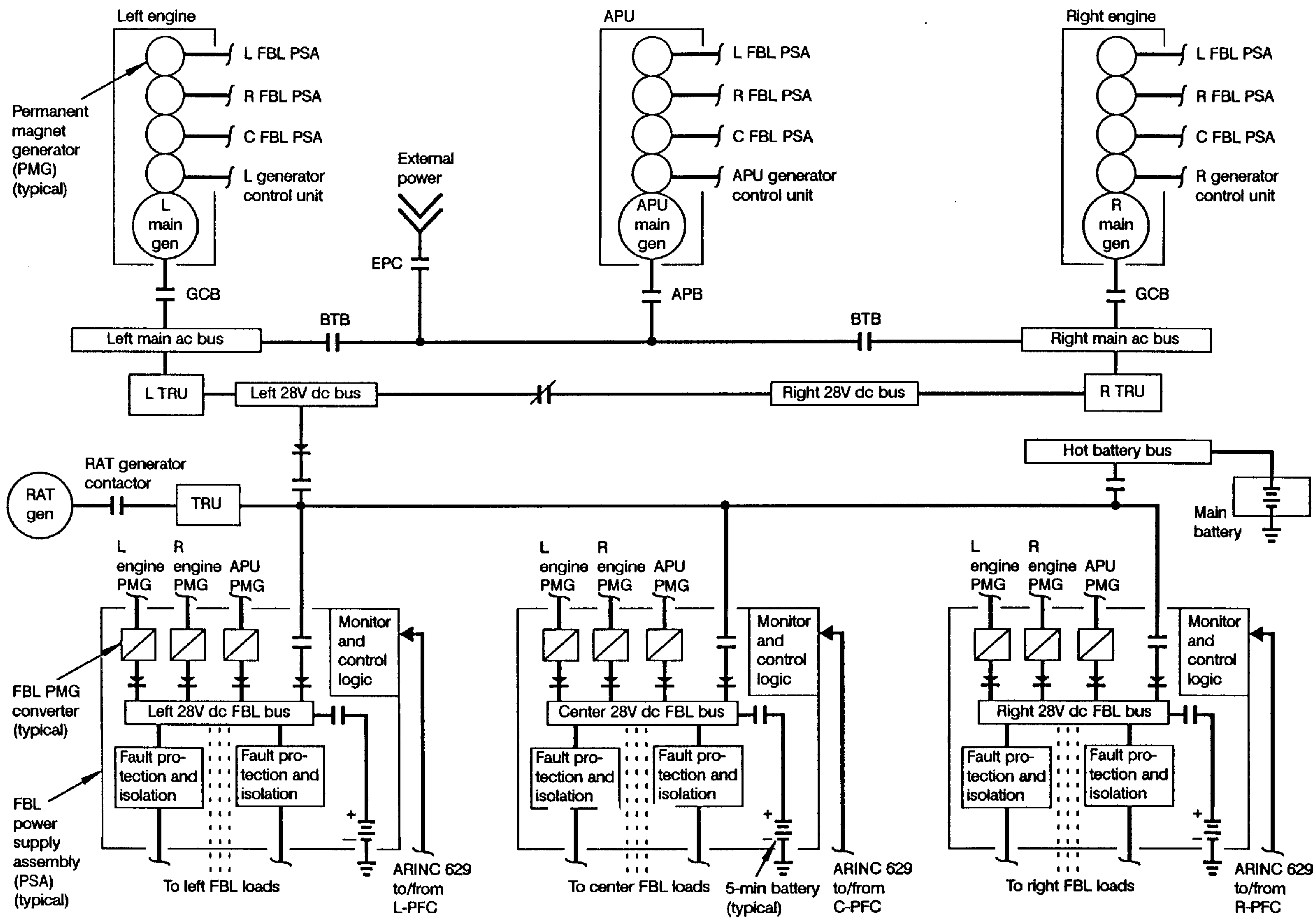

Figure 3-5. Fly-by-Light Electrical Power System

g. Displays

The engine indication and crew alerting system (EICAS) computers and display units will need modification and the display units must be suitably shielded against HERF and lightning.

h. Interface Adapter Units

Three IAUs will provide the signal interfaces between the FBL ARINC 629 buses and 757 equipment. Signals originating from components on the ARINC 629 bus and required by 757 equipment will be received by the IAUs, converted into the format compatible with existing 757 equipment (analog or ARINC 429), and consolidated into electrical connectors compatible with existing connector interfaces. Conversely, signals originating from 757 equipment and needed by components on the ARINC 629 buses will be received by the IAUs, converted into ARINC 629 format, and transmitted onto the respective ARINC 629 buses.

i. Optohydraulic Actuators

Phase III of the FBL flight control system will include optically powered, direct, optohydraulic actuators. One approach would be photovoltaic generation of electrical power to activate hydraulic control and shutoff valves. A light source located in the ACE would couple optical power via a fiber onto a photovoltaic solar cell located in the actuator. The power generated would be conditioned to levels sufficient to drive a control valve. Feedback signals via optical transducers would modulate the command signal and achieve loop closure. Design tradeoffs would still have to be conducted on the following items (i.e., shortfalls): cable, photovoltaic cell efficiency, response time, conditioning circuit efficiency, and the control valve driving format and efficiency. The cable could contain a single, large (greater than 250 μm) core fiber or a bundle of small fibers. The bundle technology has better installation considerations, but larger losses at the connectors. The cell and conditioning circuit would be chosen to maximize efficiency. Boeing's High Technology Center has recently developed high-efficiency photovoltaic cells that are expected to provide 60% to 70% efficiency when used with 820-nm laser diodes. A frequency or pulse-width modulation driving format is preferred to amplitude control, to avoid problems with interconnect losses.

4.0 FIBER-OPTIC SHORTFALLS AND GAPS

a. Fiber-Optic Cable Development (qualification testing during the second half of 1990).
Shortfalls:
1. Mechanical performance.
2. Number of industry sources.
3. Cost.

Many currently available fiber-optic cables survive well under temperature testing, but different thermal coefficients of expansion in the materials induce enough stress in the fiber to increase optical losses significantly enough to affect the operating margin. So far, there are only a handful of fiber and cable manufacturers that sell cabled fiber that may meet industry requirements. Of these companies, only one cables the type of fiber needed to produce the fiber-optic data bus couplers, and the cost of this process is expensive due to limited production runs.

b. Fiber-Optic Splice Development (qualification testing during the second half of 1990).
Shortfalls:
1. Protection systems (mechanical performance).

Gaps:
1. On-aircraft splicing equipment (production and maintenance).
2. Number of equipment sources.

The optical splice loss in the bus is one of the critical factors affecting the number of terminals possible and/or the operating margin. Boeing Commercial Airplanes is currently aware of only one company making a fusion splicer adequate for a 400-μm bus fiber. This splicer is not usable in an airplane environment due to process complexity and lack of portability and durability. Excellent splices have been produced in the lab with an existing fusion splicer, but the electrode lifetime was extremely short. Portable fusion splicers that can automatically align the fibers and consistently deliver the power to fuse bus fiber must be developed before splices with acceptable optical and mechanical performance can be installed on airplanes.

Another component of the splice that needs further development is the splice protection system that goes around the fiber once the fiber is fused. Thermally stable splice housings need to be developed.

Field repair mechanical splices with low loss need further development to ensure compatibility with the dimensions of the fiber-optic cable, long-term reliability, ease of field installation, and restoration of the cable strength.

c. Contacts (qualification testing during the second half of 1990).
Shortfalls:
1. On-aircraft termination equipment (production and maintenance).

2. Limited number of equipment sources.
3. Cost.

It is generally agreed that the epoxy or polish-type fiber-optic connector contact common today is unacceptable for airplane use due to the long assembly time involved and the poor long-term mechanical performance (i.e., thermal stability) of the epoxies used. Alternative contacts are being developed that do away with the polishing process and eliminate the stability problems associated with the epoxy. Only one or two companies have thus far announced versions considered suitable for airplane use.

d. Connectors (qualification testing of MIL-C-38999 series scheduled for completion in early 1991).
Shortfalls:
1. Optical performance over temperature.
2. ARINC 600 rack and panel connectors.

Several companies have developed a fiber-optic contact designed to fit a standard electrical MIL-C-38999 connector, and one has developed a fiber-optic version of the Boeing standard series 26500 connector. The optical performance of these connectors over temperature needs to be improved. Similar development of ARINC 600 rack and panel contact or connectors are needed. One company has announced they can make fiber-optic versions of many different connectors, including the Boeing standard series MIL-C-26500 and MIL-C-83723, as well as ARINC 600, if the demand is high enough and funding is available.

e. Handling and Installation Procedures (Operations Technology's procedures scheduled to be completed by end of 1990).
Shortfalls:
1. Clamps and ties.
2. Bend radius limiters.
3. Bulkhead feedthroughs.

Many of the details of handling and installation need to be worked out, including those listed previously. However, these are not expected to require any new technology development, only engineering design time.

f. Maintenance Training and Equipment
Shortfalls:
1. Trained maintenance personnel.
2. Repair procedures.

Maintenance training is an integral part of any new technology development, but it is absolutely critical for the success of fiber-optics on commercial transport airplanes.

The documented experience of industry to date indicates that, when handled and supervised by personnel with fiber-optic training and experience, fiber-optic systems in airplanes continue to perform well after installation. However, when systems are handled by maintenance personnel with no or minimal fiber-optic training and experience, the systems often fail due to dirty connectors, fiber damage, and so forth. The maintenance community *must* be properly trained in the handling of fiber optics.

Equipment, methods, and processes for repairing and testing data buses and replacing couplers must be developed. Fusion splicers and connector termination methods that can be used easily in the field will be essential for proper fiber-optics maintenance.

g. Receiver and Coupler Improvement (preproduction tests scheduled to be completed by 3rd quarter of 1990).

   Shortfalls:
   1. Operating margin.
   2. Terminal count.
   3. Environmental performance.
   4. Number of sources.

   Using the linear bus architecture with the ARINC 629 protocol, a 30- to 40-terminal bus (with margin) is currently achievable with acceptable environmental performance from at least one source. In order to increase terminal count beyond the 30-to-40 range with the ARINC 629 protocol, a fundamentally different receiver must be designed. Optical feedback, which may increase receiver sensitivity by 10 to 15 dB with corresponding improvement in dynamic range, would be one such approach. Several papers reporting experimental receiver performance using optical feedback have been published. A 10-dB receiver sensitivity improvement could increase the terminal count by about 30.

h. High-Temperature Engine Harness (qualification tests scheduled to be completed by 3rd quarter of 1990).

   Shortfalls:
   1. High-temperature and vibration components.

   Gaps:
   1. Firewall penetration.

   Some of the components discussed (especially connectors and contacts) must be further developed to withstand the higher temperature and vibration requirements of the engine nacelle. A method of firewall penetration must be developed that will pass the fibers through the firewall while maintaining full firewall integrity.

i. New Optical Source Development

Present light-emitting diode (LED) outputs degrade over time due to increased nonradiative recombination. It may be possible to develop LEDs with a different structure to reduce this degradation and increase LED efficiency, reliability, and lifetime. In addition, recently reported quantum well devices may be capable of launching significantly higher power into fiber than today's commercially available LEDs, while providing similar robustness in avionics environment.

j. Optical Sensor Development

Present sensor systems use LEDs for the optical source to withstand the avionics environment. Sources with increased power will improve the detector signal-to-noise ratio. It is expected that quantum well laser diodes will provide higher power than LEDs and environmental robustness. Laser diodes will also provide a source of coherent light for use in fiber-optic interferometers. The interferometers sensors can provide extremely high sensitivity and reduced noise levels, but need a high-power, coherent source. Interferometric sensors will additionally require the development of single-mode fiber and connectors suitable for the avionics environment. The major difficulty foreseen with single-mode technology is the susceptibility of the small core dimensions (5 to 10 μm) to contamination in the connector intensive avionic systems of today.

Lasers may be used in 1995 sensor designs, and in single-mode technology by the year 2000.

Digital transducers will continue to see incremental improvements in throughput losses, performance, and reduced size and weight. Decreased losses improve the power budget or allow the available light to be split among more channels. With more channels, the resolution can be improved, but improvements in the optical designs of the code plates and fiber apertures must happen concurrently to keep the size and weight acceptable. The manufacturability of the sensors must also keep pace to take advantage of the improved performance and control costs.

Analog transducers will incrementally improve in design and manufacturing to provide accurate and repeatable performance with size and weight competitive to electrical transducers. The major obstacle is path losses for reference and signal channels, which limit the accuracy of the output. Several companies and university groups are working to produce analog sensors that provide a frequency output with a bandwidth of 10 to 100 kHz using silicon micromachined resonators, which will provide good resolution and a simple interface.

In general, sensors with good performance to cover a wider range of sensing applications are necessary, with testing to prove the reliability limits of the sensors. The most important reliability concern for position sensors is to provide long-lived environmental seals that exclude contaminants and fluids from the optical path. The sensor manufacturers must work to provide this range of sensors with a standard set of optoelectronics, rather than unique circuitry for each application. The widest range of sensing functions can be provided by wavelength modulation (i.e., filtering the light passing through the sensor). Two components must be developed to exploit this technology: a monolithic, broad-spectrum LED covering 750 to 900 nm; and a small, high-resolution wavelength multiplexer with 70% to 90% efficiency. The standard interface supports an integrated avionics computer system (IACS) standardization concept for integrating many of today's individual line replaceable unit (LRU) systems.

k. Optohydraulic Actuators

The major shortfall of optohydraulic actuators is providing sufficient light to power electronics of hydraulic controls. High-power laser diodes appear to be the choice for the year 2000, but they are currently not robust. They are also expensive, have short lifetimes, and require a heavy power supply for current drive and temperature control. Low-loss optical switches are needed to modulate the high-power light from a single laser, coupled via fiber, to several control valves. Efficient photovoltaic generation of power will incrementally improve and control valves with lower power requirements will be developed. Alternative, more efficient, control methods may become possible, but no clear technology path has emerged.

5.0 CERTIFICATION ISSUES

The certification issues pertinent to the defined fly-by-light (FBL) flight control system are the safety and integrity of the system using the new, unproven, fiber-optic components.

The certification process is defined as the process of planning and performing the analyses and tests and generating the system description, analyses, and tests documentation and/or demonstrations to support the regulatory agency in the certification of the system.

5.1 VERIFICATION ISSUES

Verification is the process of testing the implementation to prove that the design has been implemented as specified and does nothing unspecified. Verification testing is usually done by the supplier. Verification issues pertinent to the defined FBL flight control system are identified in the following paragraphs. Use of the advanced requirements specification methodology (as developed under contract NAS1-18586) was considered.

The biggest verification problem is proving that the system does nothing unspecified. This involves traceability from requirement specification through implementation and verification testing and vice versa. Adding compatible methodologies and tools for the design, analysis, evaluation, implementation, and verification processes would eliminate the traceability problem.

A second part of this issue is the inability to perform detailed tests on very large scale integration (VLSI) components, particularly standard items such as processors and memories. This inability to test in detail affects not only the ability to detect unspecified functions, but also the ability to test for latent failures. This provides a dilemma, since configurations implemented with only VLSI components are typically necessary to provide the reliability necessary to satisfy safety and availability requirements.

Another verification issue is the high-energy radio frequency (HERF) susceptibility. Even though fiber optics is being used, there is still the question of line replaceable unit (LRU) susceptibility around openings such as the fiber-optic input ports. Susceptibility on the power lines and the effects of the required filtering of the induced noise are also questioned.

A third verification issue is the integrity of the fiber-optic cabling in the commercial airplane environment. Vibration and temperature cycling over long periods are the major concerns.

The whole question of long-term environmental effects on items such as connectors, splices, shield grounds, and so forth, is also an issue.

5.2 VALIDATION ISSUES

Validation is the process of testing the implementation to prove that the system, as implemented and installed in the vehicle, adequately complies with all of the general system requirements. Validation testing is conducted by the aircraft manufacturer. A validation issue pertinent to the defined FBL flight control system is the performance of the system using the new, unproven, fiber-optic components. A methodology and automated tool for the validation process that is compatible with the verification process methodology and tool would help to solve this problem.

6.0 DEVELOPMENT PLAN

The Fly-by-Light (FBL) Technology Development Plan will be divided into three different sections: (a) tasks fully funded by NASA, (b) tasks funded partially by NASA, and (c) tasks not funded by NASA.

6.1 TASKS FULLY FUNDED BY NASA

a. The prime contractor will maintain the master schedules and track the critical path of the FBL Technology Development Plan. The contractor will also coordinate the tracking of progress and resolution of action items.

b. The prime contractor and the suppliers will develop prototype ARINC 629 bus configurations for the NASA Transport Systems Research Vehicle (TSRV).

c. The prime contractor and the suppliers will perform detailed design and prototype development of distributed actuator control electronics (ACE) for the FBL flight control system with fiber-optic ARINC 629 signaling.

d. The prime contractor will analyze system level performance and failure modes and effects analysis of the full-up FBL flight control system.

e. The prime contractor will develop laboratory test, system integration and flight test plans and detail procedures.

f. The prime contractor will procure fiber-optic equipment needed to support laboratory and flight tests on the NASA TSRV, including spares.

g. The prime contractor will design and develop flight deck controllers for the FBL flight test on the NASA TSRV.

h. The prime contractor and the suppliers will develop prototype optical sensors and optohydraulic actuators for the NASA TSRV.

i. The prime contractor will conduct detailed laboratory tests, system integration tests, and flight test on the NASA TSRV of fiber-optic ARINC 629 components, optical sensors, and optohydraulic actuators.

j. The prime contractor will develop fault tolerance techniques for the FBL system on the NASA TSRV.

6.2 TASKS FUNDED PARTIALLY BY NASA

a. The prime contractor and the suppliers will update their own laboratory systems to accommodate optical ARINC 629 interfaces.

b. The prime contractor will select an appropriate fiber-optic sensor solution for each kind of optical sensor.

c. The prime contractor will prepare detailed specifications for optical sensors and optohydraulic actuators.

d. The prime contractor will conduct qualification testing of optical sensors and optohydraulic actuators.

e. The prime contractor will prepare a certification roadmap for the FBL flight control system.

6.3 TASKS NOT FUNDED BY NASA

a. The prime contractor with other members of the industry will establish data bus standards for fiber optic cable, connectors, splices, and so forth.

b. The prime contractor will conduct qualification testing of data buses, transceivers, and couplers.

c. The prime contractor will develop processes and procedures for fiber cleaving, splicing, splice protection, and functional test.

d. The prime contractor will develop installation and inspection processes and procedures for FBL elements on an airplane.

e. The prime contractor will develop connector contact cleaning and repair techniques and procedures for splicing of cables.

f. The prime contractor will conduct environmental tests of sample fiber-optic couplers and splices and of full 40 terminal bus configuration.

g. The prime contractor will delineate pigtail and packaging requirements for data bus optical transceivers.

h. The prime contractor will work with a few airlines and conduct inservice evaluation of specific fiber optic components to gather reliability and durability data and address maintenance issues.

7.0 NASA TSRV MODIFICATION

A description of the Advanced Transport Operating System (ATOPS), as currently understood, will first be provided. Then the proposed changes to incorporate the fly-by-light control system will be identified.

7.1 ATOPS DESCRIPTION

ATOPS includes the Transport Systems Research Vehicle (TSRV), the Experimental Avionics Simulation and Integration Laboratory (EASILY) and the Experimental System.

7.1.1 TSRV Description

TSRV is NASA Langley Research Center's (LaRC) B-737 airplane, NASA 515, the flying testbed for the Experimental System. The TSRV, with the Experimental System installed, is shown on figure 7-1.

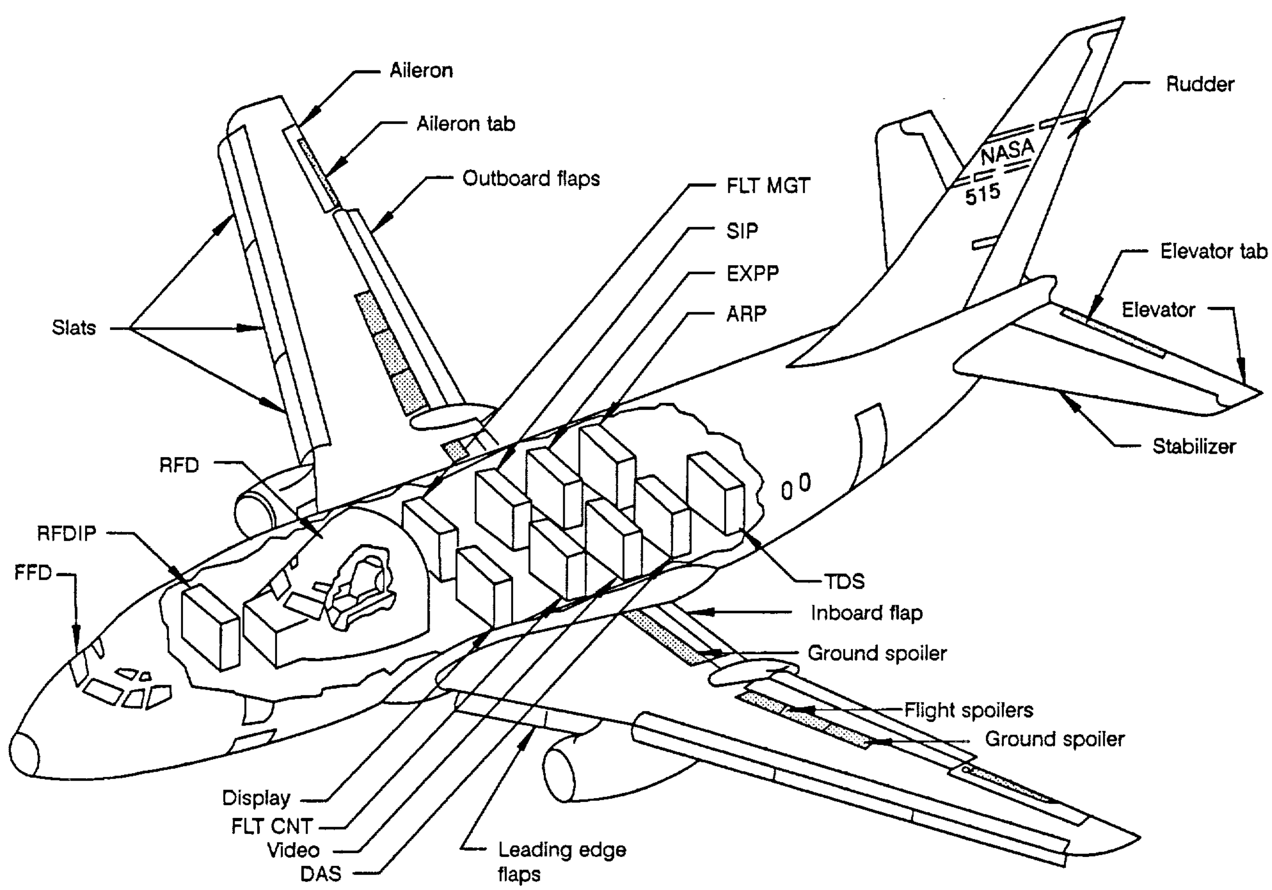

Figure 7-1. Experimental System on the Transport System Research Vehicle

12-U90249R1-6

The TSRV flight control surfaces proposed to be affected by the fly-by-light (FBL) installation are shown on Figure 7-2. These include the elevators (figs. 7-3 and 7-4), the stabilizer (figs. 7-5 and 7-6), the ailerons (figs. 7-7 and 7-8), the spoilers (fig. 7-9), the rudder (figs. 7-10 and 7-11), and the flaps and slats (fig. 7-12).

7.1.2 EASILY Description

EASILY is the laboratory test bed for the Experimental System. This facility is designed to support thorough and realistic testing of the major subsystems of the Experimental System. EASILY consists of a simulation of the TSRV (including its aerodynamics and all of the basic airplane sensors and actuators which interface with the major subsystems of the Experimental System, the sensors of the Experimental System that interface with its major subsystems, and Earth referencing of the appropriate sensor data) and the interface/testset between the simulation and the major subsystems to be tested.

7.1.3 Experimental System Description

A block diagram of parts of the Experimental System connected by digital autonomous terminal access communication (DATAC) is shown on figure 7-13. The Experimental System consists of all of the

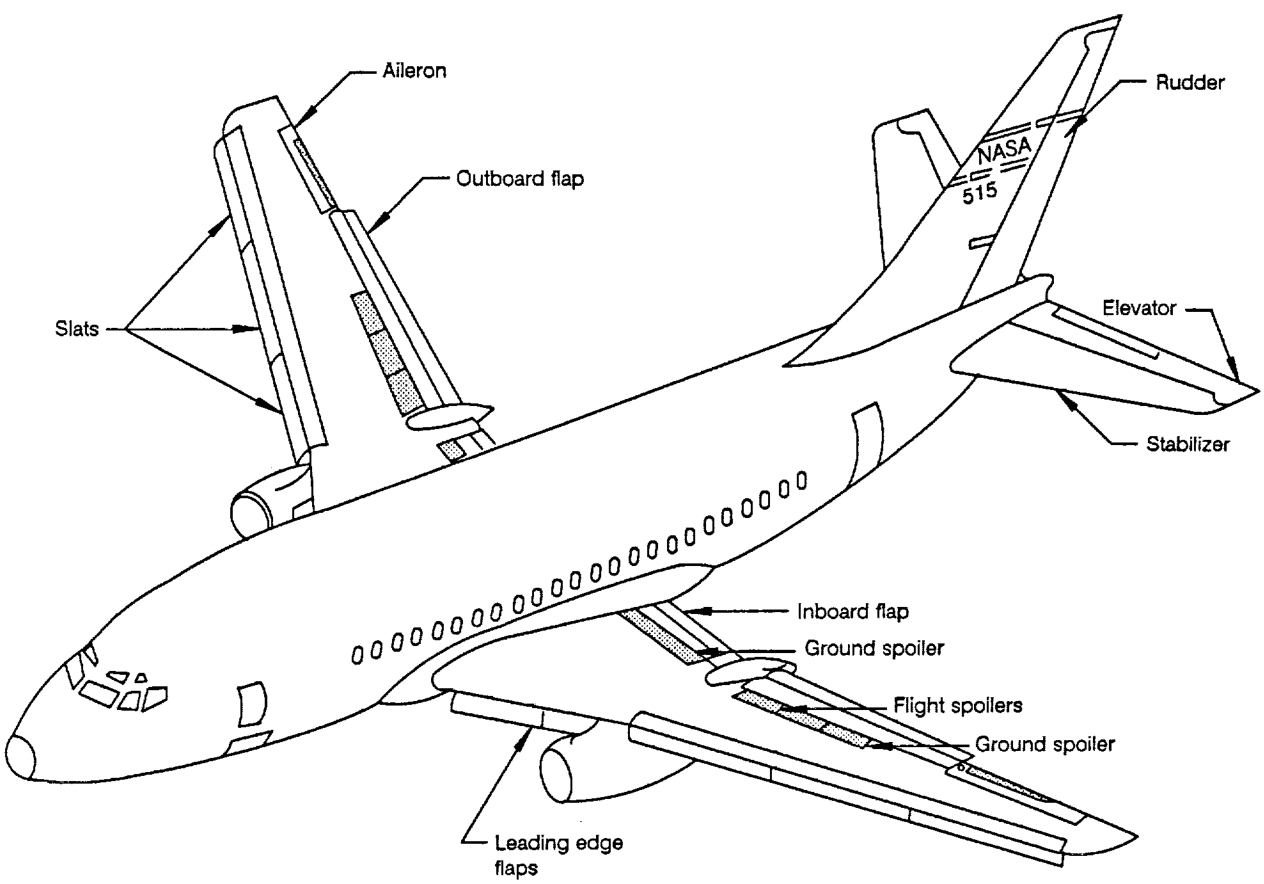

Figure 7-2. Flight Control Surfaces Affected by FBW (Transport System Research Vehicle)

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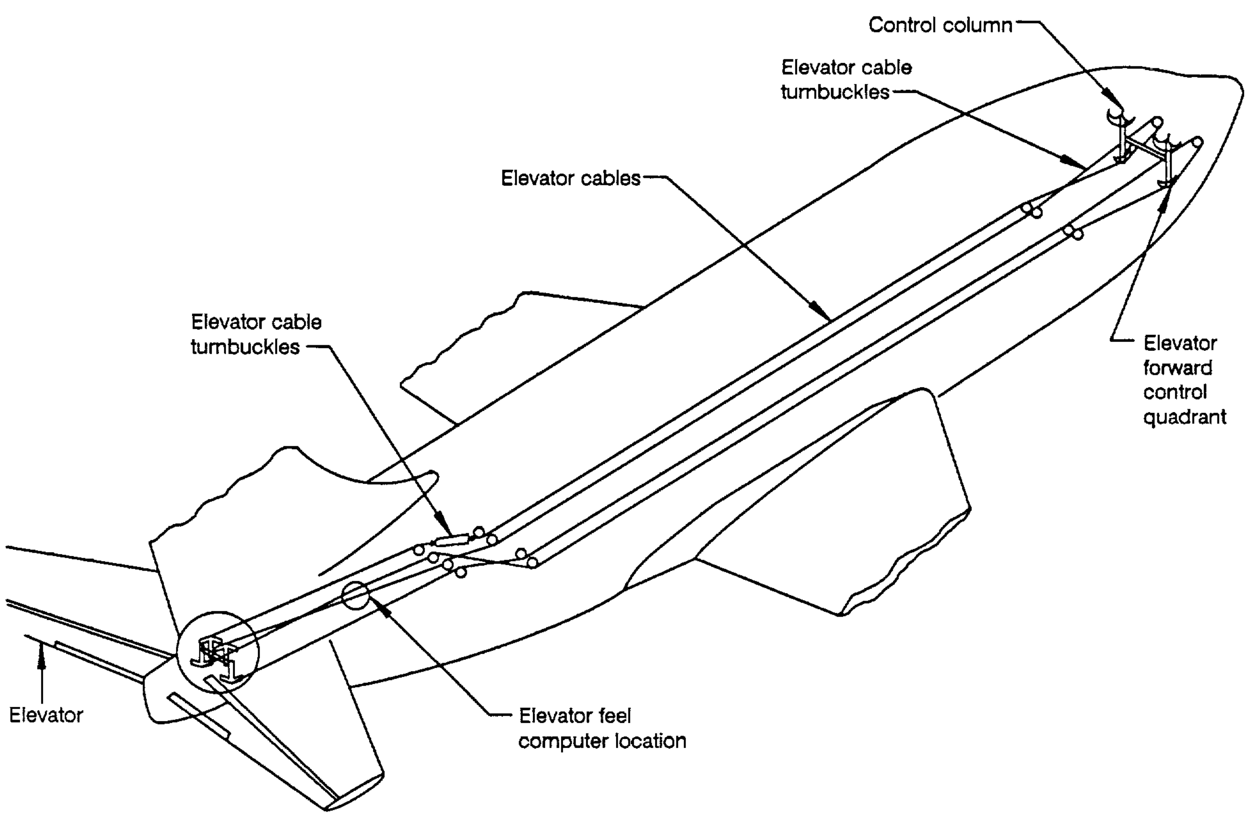

Figure 7-3. Component Locations Longitudinal (Elevator) Control System

12-U90249-8

experimental equipment on the TSRV. This includes part of the right side of the forward flight deck, the DATAC bus, the VME bus, and the following:

a. The research flight deck interface pallet (RFDIP). This pallet contains the interface electronics and servo electronics between the research flight deck (RFD) and the airplane.

b. The research flight deck. This is an experimental cockpit that can be relatively easily reconfigured as experiments require, while maintaining the forward flight deck in its basic configuration where the safety pilots can override and disengage the RFD flight control functions. The RFD is a palletized installation with no mechanical control connection with the basic airplane. The RFD contains eight D-format Sperry display units (DU) that are driven by three display host electronics units (DHU) via a serial digital bus. The DHU is in turn driven by the Norden display host computer (DHC) via a high-speed serial digital bus. A data link display with touch panel control and Lear Siegler control display units (CDU) are also installed. A McFadden side arm controller (SAC) is being installed on the left side with the old Brolley handles remaining on the right side until the second SAC is installed. When the second SAC is installed, the capability for coupled and backdriven SAC operation will exist.

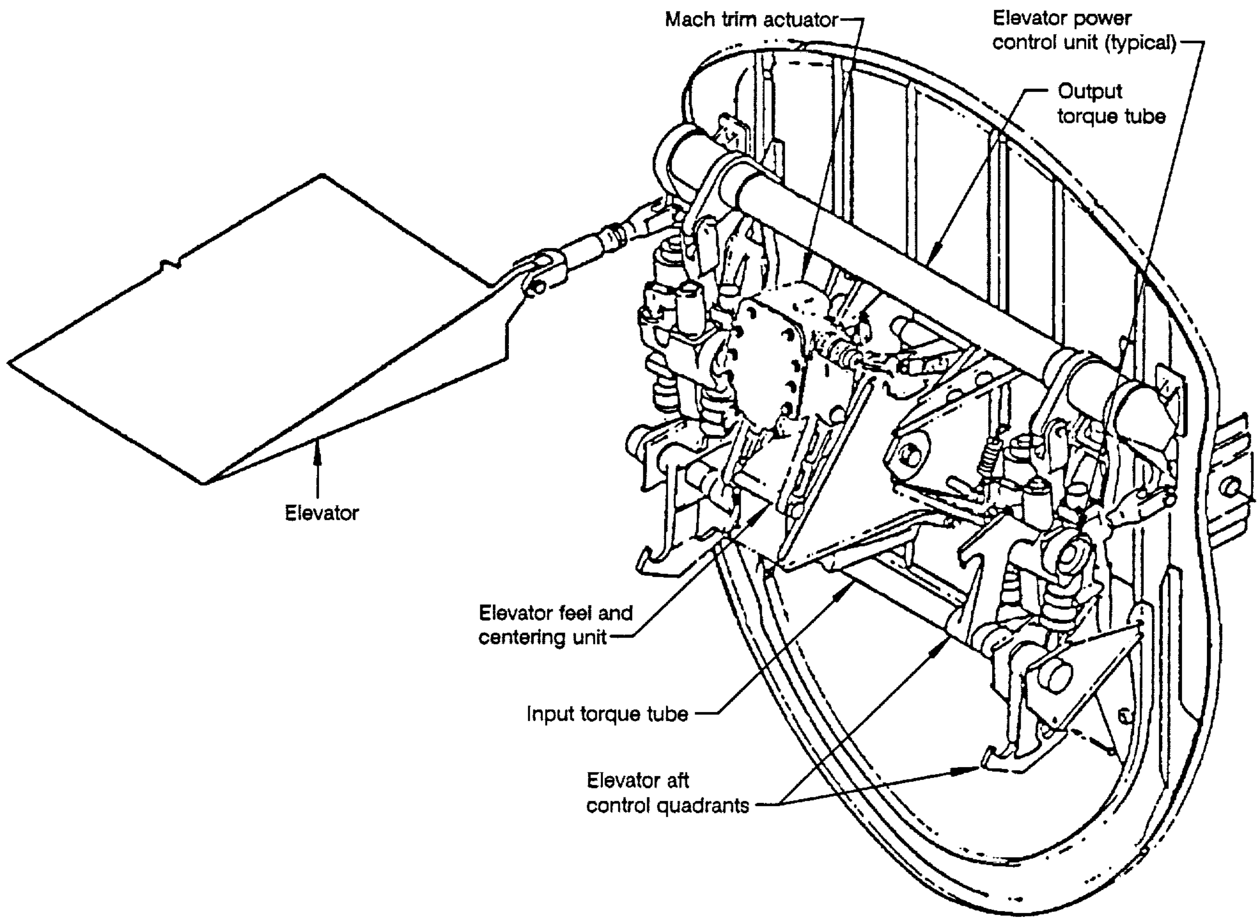

Figure 7-4. Component Locations Longitudinal (Elevator) Control System

12-U90249-9

c. The air data inertial reference unit (ADIRU) manufactured by Honeywell and located in the forward cargo bay.

d. The flight management (FLTMGT) pallet.

e. The display (DISPLAY) pallet. This pallet contains the terminal and disk drive for the Norden DHC.

f. The sensor interface pallet (SIP). This pallet contains the interface between the Experimental System and the remotely located sensors such as Instrument Landing System (ILS), Microwave Landing System (MLS) and Global Positioning System (GPS).

g. The flight controls (FLTCNT).

h. The experimenter's pallet (EXP P). This pallet contains displays and stripchart recorders that can be configured to support the experiments being run. It also contains a Digital Equipment MicroVax II that is connected to two Norden hardened PDP11/70 computers (located in the aft cargo bay below

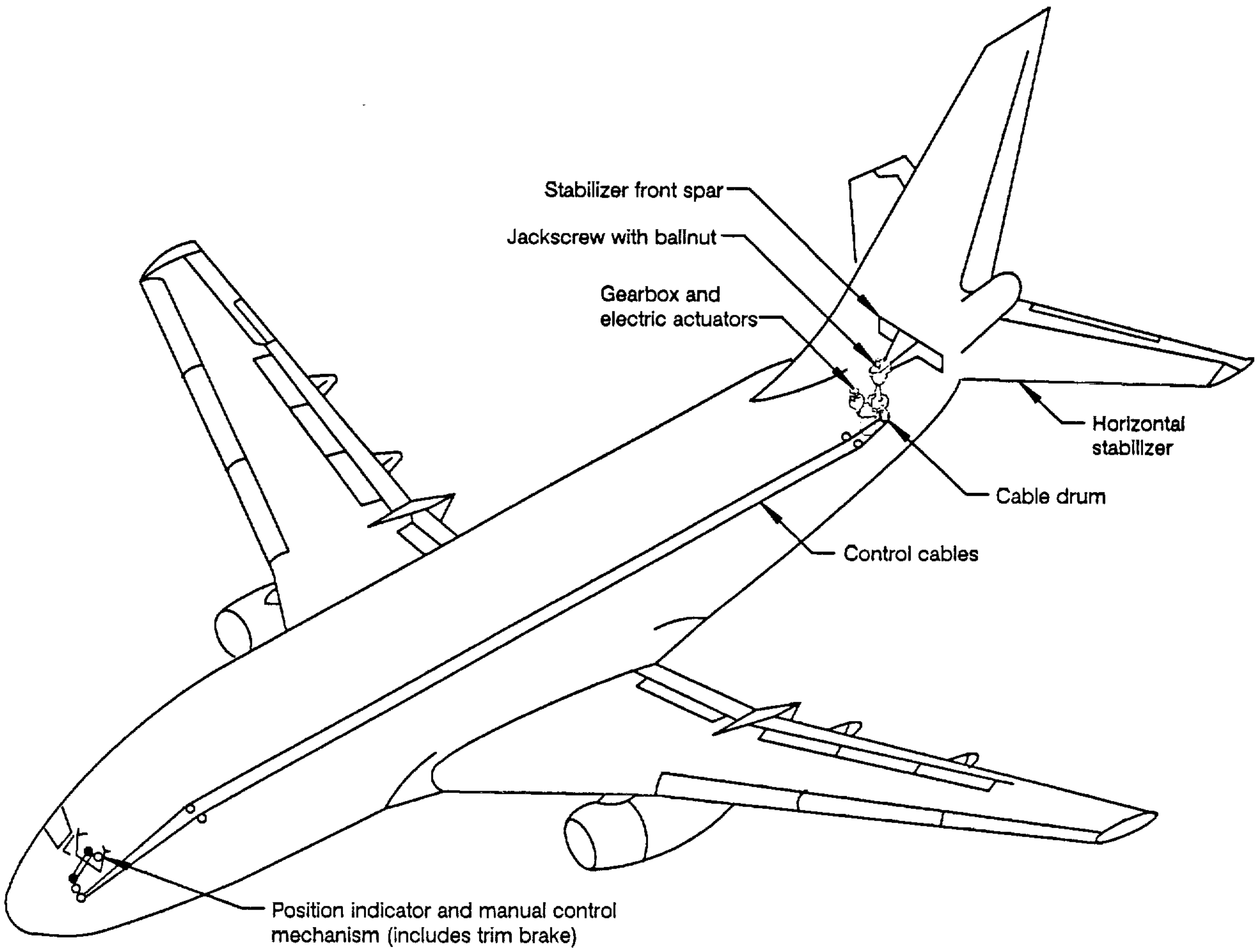

Figure 7-5. Component Locations Longitudinal (Horizontal Stabilizer) Trim Control System

12-U90249-1

the EXP P) via a short, high-speed digital bus. The MicroVaxII provides the flight control and the flight management computations, including the 4D navigation and guidance computations.

i. The video (VIDEO) pallet. This pallet contains the equipment required to buffer and record the video data displayed on the Sperry DUs in the RFD.

j. The avionics research pallet (ARP). This pallet contains the LISP artificial intelligence (AI) Processor (Hummingboard) which is the task tailored flight information manager for the processed flight data (PFD) displayed in the RFD.

k. The data acquisition system (DAS). The DAS pallet contains the PADS and the DATAC data divider. The PADS records patched, pulse-code modulated analog and programmer-selectable serial digital data. The DATAC data divider provides the capability to select and store (on magnetic tape) 450 DATAC bus parameters every 50 ms.

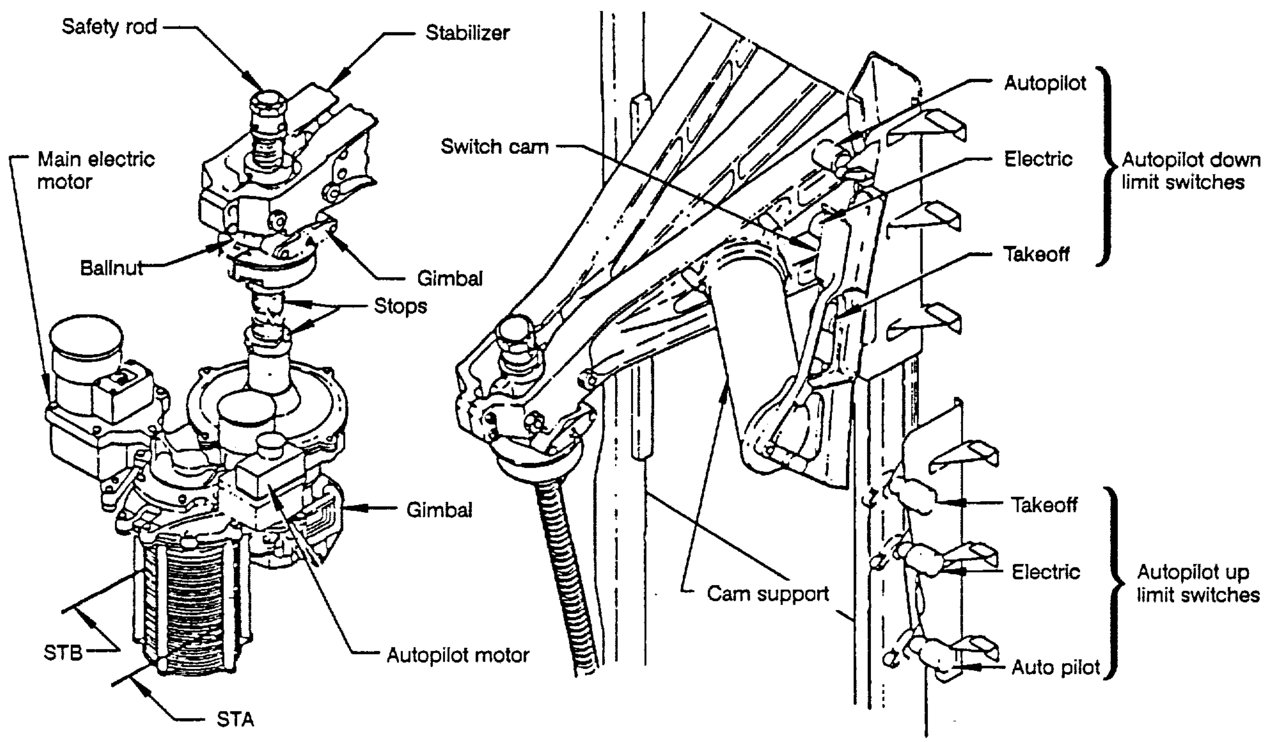

Figure 7-6. Horizontal Stabilizer Trim Control System—Aft Assembly

12-U90249-11

l. The thermal detection system (TDS). The TDS pallet contains the thermal alert system and two associated printers. The thermal alert system monitors thermocouples located in strategic locations in the airplane and provides maintenance data and an alert, if warranted.

The two Norden computers are located in the aft cargo bay below the EXP P. One of these computers is the DHC for the Sperry display system. The other is primarily a data link processor. It provides all data link management processing, including the data link display touch control panel processing. It also processes the ARINC communications addressing and reporting system (ACARS) ATC up/down link. Packet data link data from the ground is also processed. In the future, satellite data link data may be processed here. Data formatting for experimenter-requested data is also processed in this computer.

Additional equipment that comprises the ATOPS experimental system is defined below:

a. VME bus interface unit (VIU).
b. Sensor interface unit (SIU).
c. Effector interface unit (EIU).
d. Interprocessor link (IPL).
e. ARINC 429 data bus (A429).
f. ARINC 568 data bus (A568).
g. RS232 data bus (RS232).

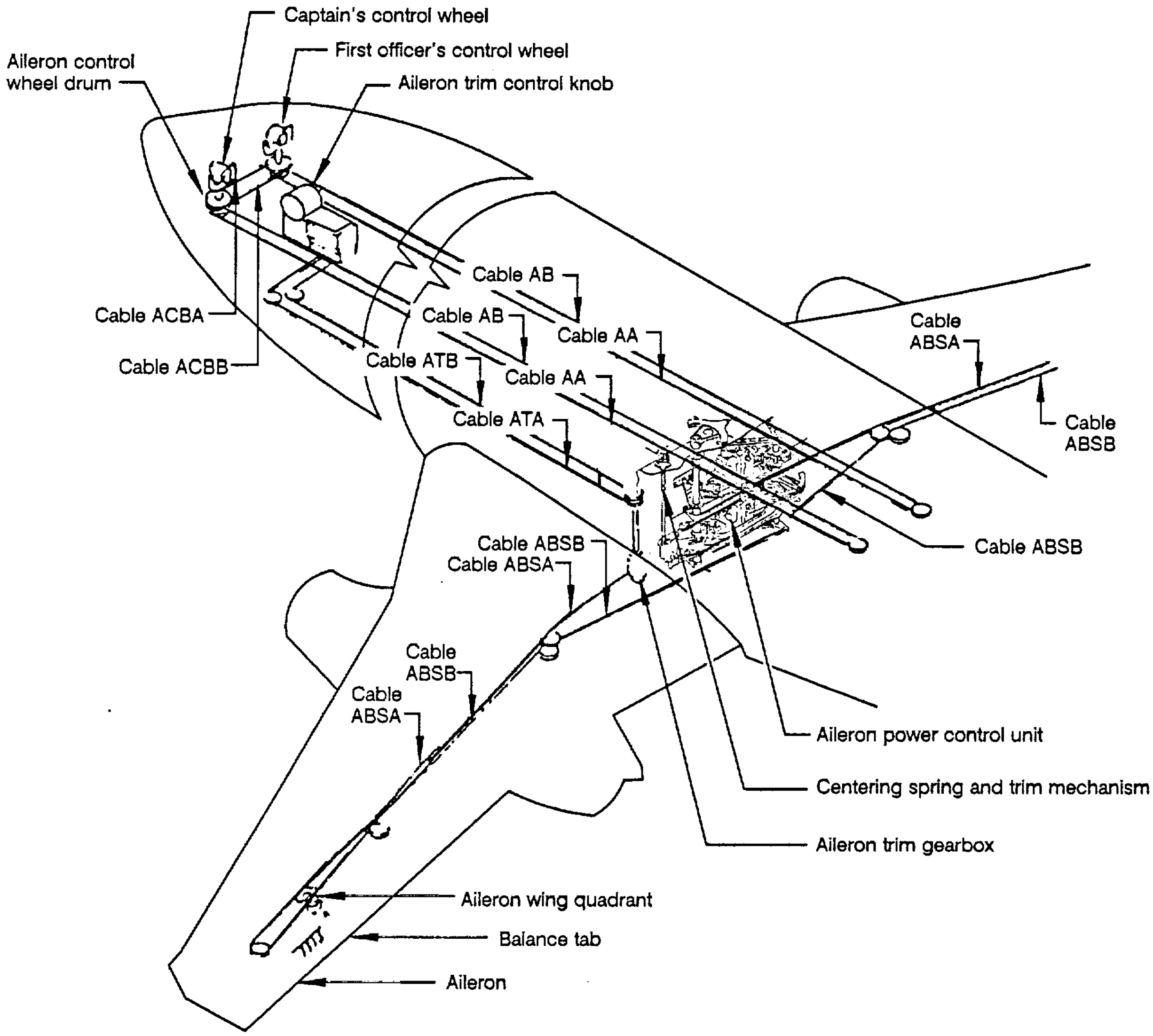

Figure 7-7. Component Locations Lateral (Aileron) Control and Trim System

h. Direct memory access (DMA) data transfer path.
i. Packet data link terminal node controller (TNC).
j. Air data inertial reference system (ADIRS).
k. Control and mode panel (CMP).
l. ARINC communications addressing and reporting system (ACARS).

7.2 PROPOSED ATOPS FLY-BY-LIGHT MODIFICATIONS

It is recommended that NASA LaRC install a highly fault tolerant, ultrareliable, flight-critical, digital FBL flight control system in the TSRV. This system should be an embedded system that replaces all of the mechanical flight control system in the aircraft. This system must be designed to satisfy all

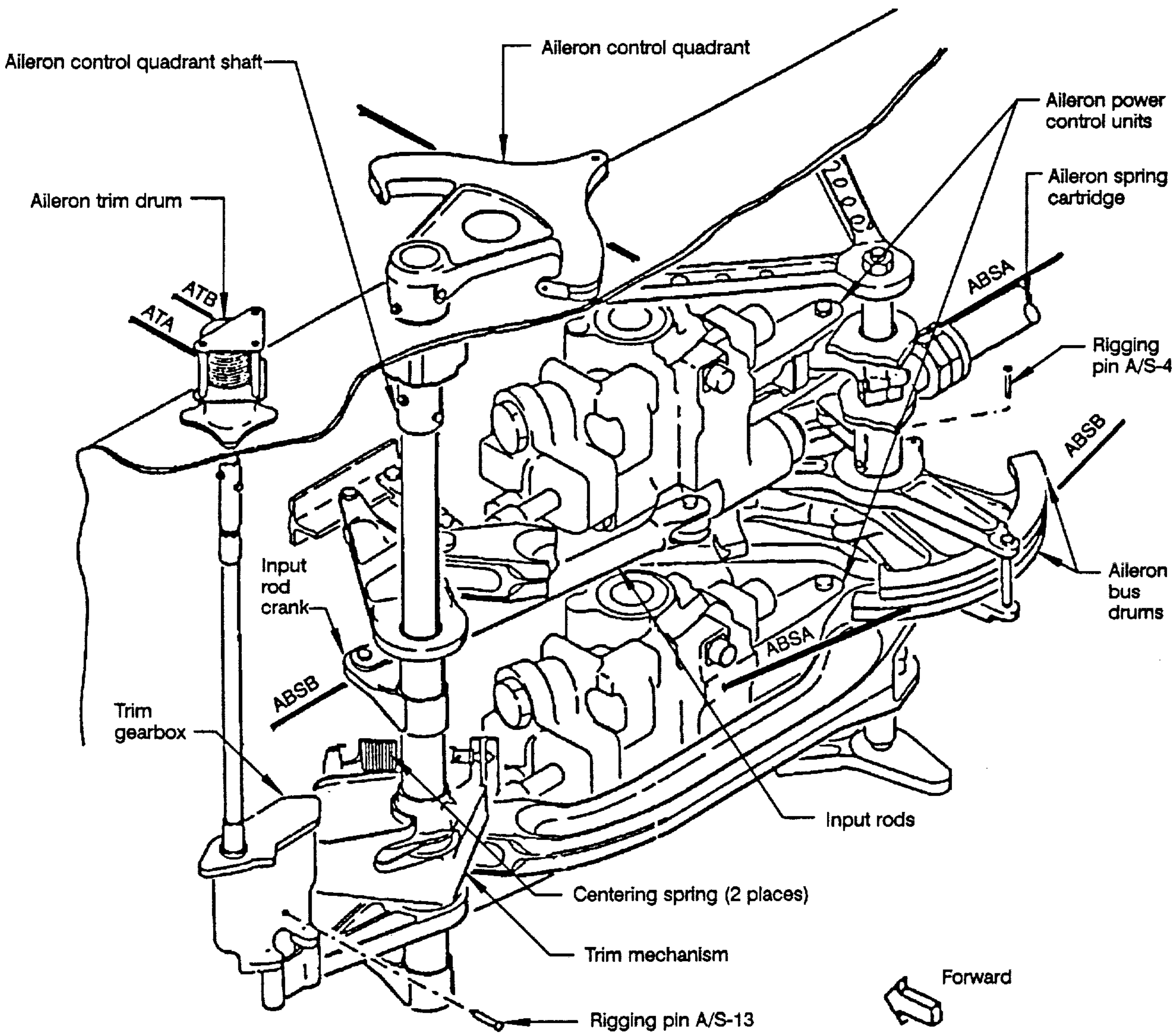

Figure 7-8. Component Locations Lateral (Aileron) Control and Trim System—Expanded View

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safety-of-flight requirements for a full-authority FBL system. It should have the capability and flexibility to perform a wide range of experiments. However, it is understood that safety-of-flight considerations will make it rather difficult to make hardware and software changes for experimental purposes.

The forward flight deck should be implemented as an FBL crew station. If there is sufficient space in the forward flight deck for the expected displays and other flight deck equipment that will be tested, the aft flight deck could be removed from the aircraft. However, if this is not the case, it will be advisable to maintain the aft flight deck.

Although the system would be eventually designed to have full authority on all aircraft axes, it may be desirable to initially implement only the rear flight deck and drive the controls through the current rear

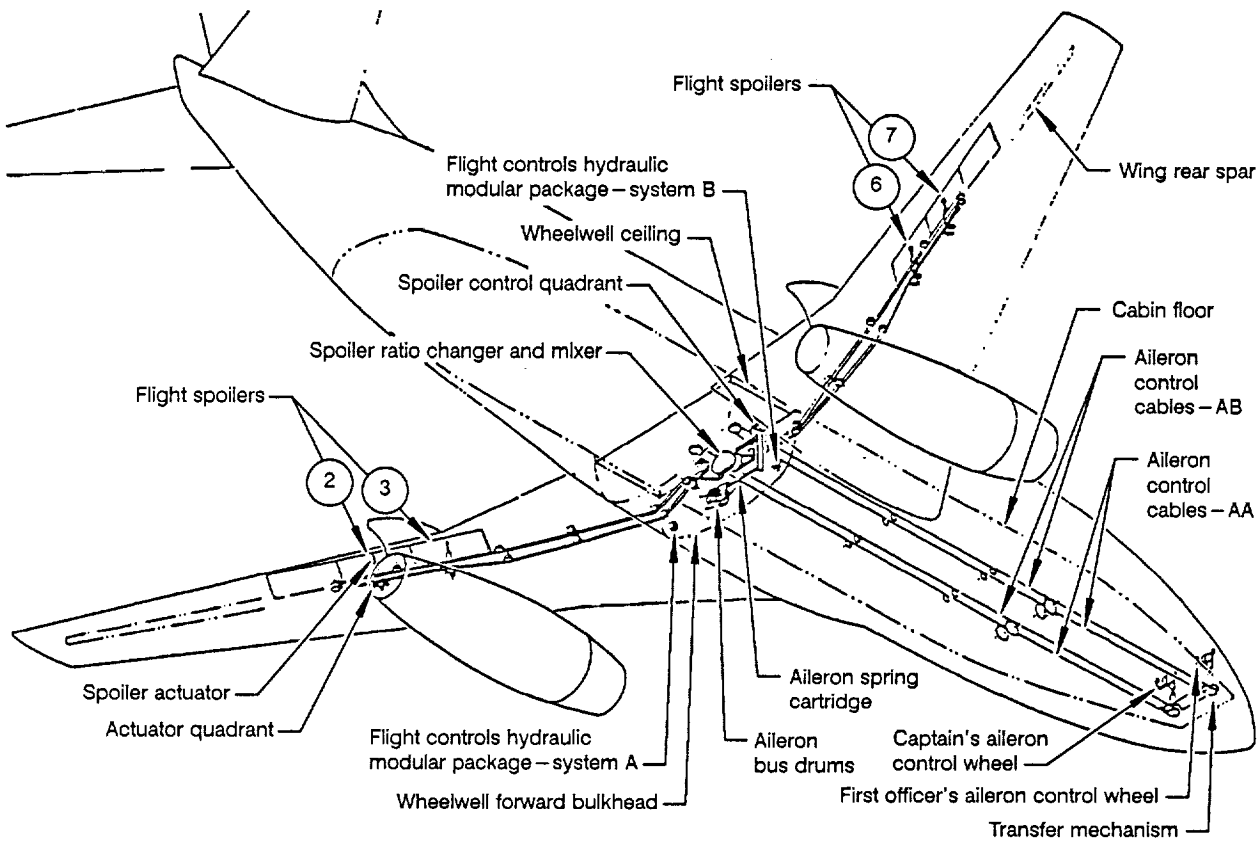

Figure 7-9. Component Locations Spoiler Control System

12-U90249-14

flight deck control actuators, which possibly could be modified to increase their authority. This would give some limited exposure to the system prior to going to full-authority operation.

7.2.1 TSRV Modifications

The FBL system will replace the existing mechanical cable, quadrant, pushrod method of providing control surface commands from the pilot. Therefore, the system must provide a comparable level of safety and thus will require a very secure installation. The FBL resources should be installed as the aircraft's primary flight control system with a high degree of integrity and not as a single, easy-to-remove entity.

The FBL system, shown in figure 3-1, consists of several primary flight computer (PFC) and secondary flight computer (SFC) computational units, pilot controller sensors and sensor interface units (PCE), actuator control electronics units (ACE), and interface adapter units (IAU) to interface with the aircraft and experimental system sensors and displays. The sensor complement includes two pilot controller sets in the forward flight deck and two in the rear flight deck. It will also contain dedicated aircraft rate, acceleration and air data inertial reference units (ADIRU) and standby attitude and air data reference unit (SAARU) with the appropriate levels of redundancy. The FBL system controls the elevators, stabilizer, rudder, ailerons, flight spoilers, flaps, slats, and engines. All communication within the FBL system

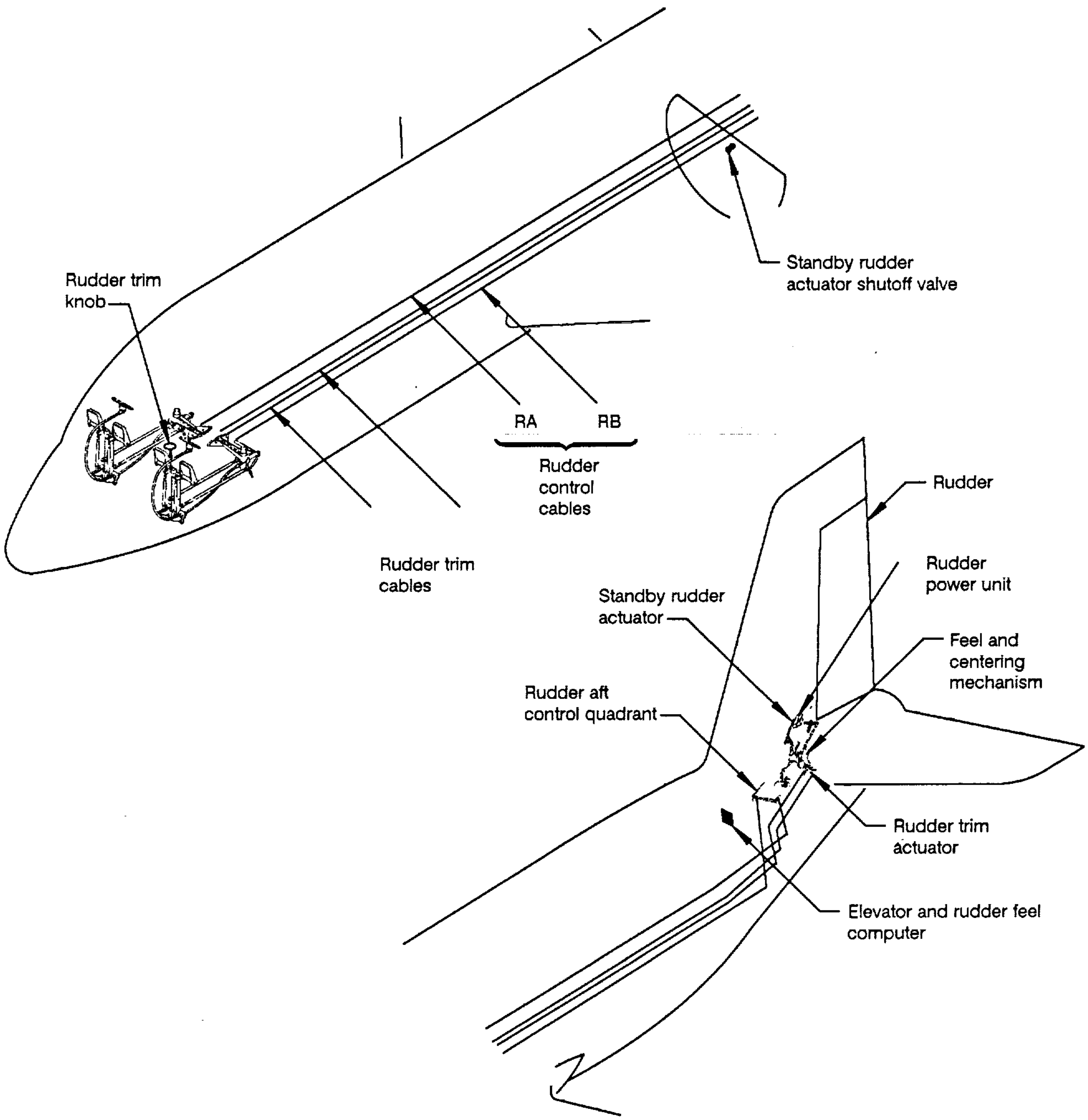

Figure 7-10. Direction (Rudder) Control and Trim System

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is over dedicated FBL DATAC buses. All interfaces with nondedicated FBL elements occur via the FBL interface adapter units. This includes interface with non-flight-critical sensors and actuation devices, autopilot, data acquisition, and displays.

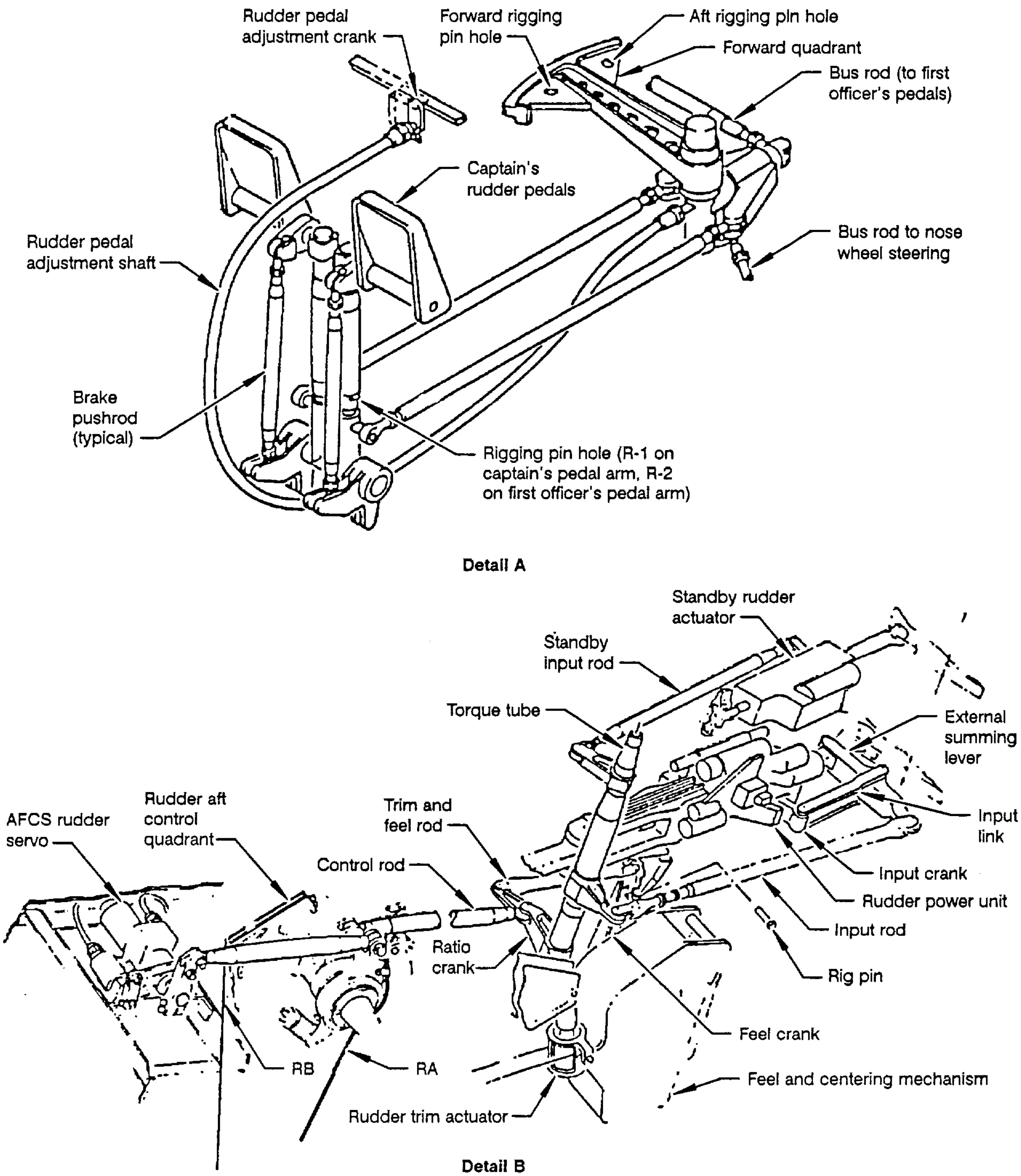

Figure 7-11. Component Locations Directional (Rudder) Control and Trim System

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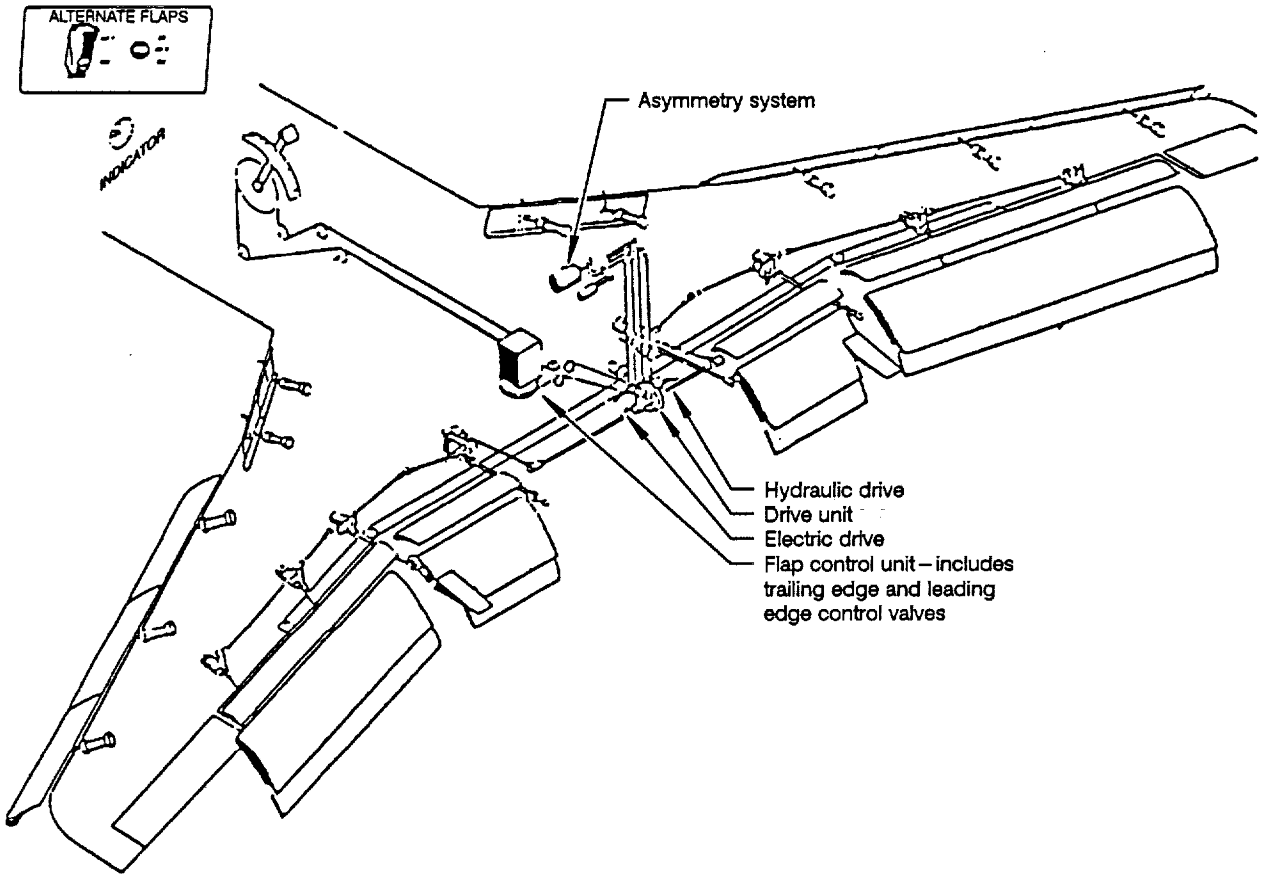

Figure 7-12. Component Locations Flap Control System

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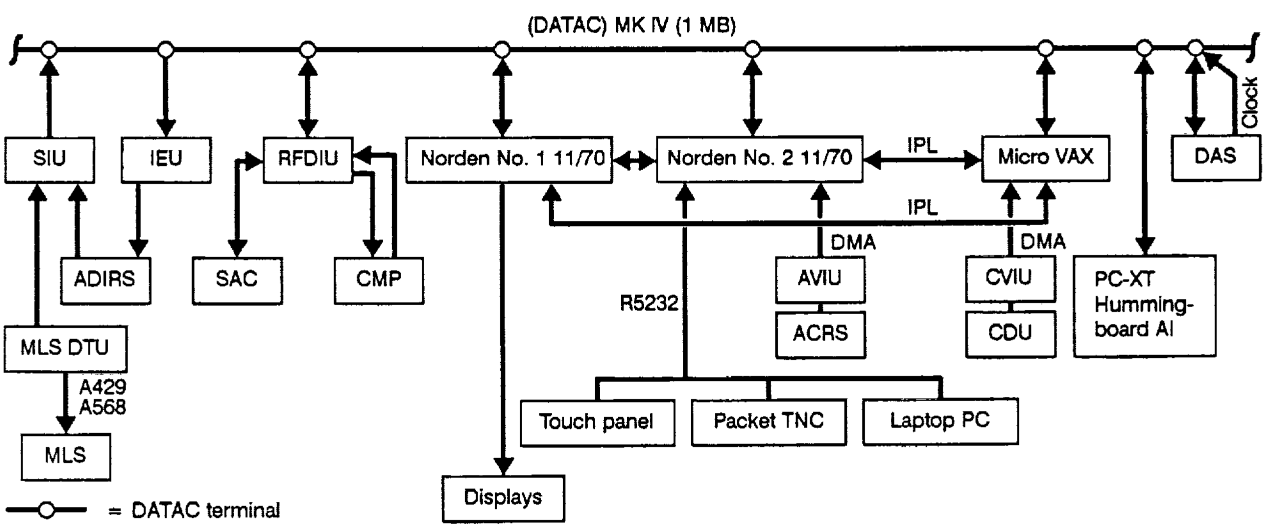

Figure 7-13. Experimental System Configuration, Late 1989

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7.2.1.1 Phase I TSRV Modifications

The initial FBL system installation will require an extensive analysis and design phase. A one-man-week preliminary evaluation concluded that the FBL control system could be installed with the following modifications to the TSRV.

a. Install a third "C" hydraulic system. This requires a new "G trap" reservoir; an electromotor pump (EMP), which may come from "B" system; and lines to a heat exchanger, a rudder, one actuator on each elevator panel, and one actuator on each aileron.

b. Remove the engine-driven generators from the engines and auxiliary power unit (APU). Replace them with generators that have three additional permanent magnet generators (PMG) in the housing dedicated to the FBL power supply assemblies.

c. Install a ram air turbine (RAT) with a hydraulic pump and a electric generator. The hydraulic pump will feed the new C hydraulic system. The generator will be converted to 28V dc and made available for use by the FBL power supply assemblies when the RAT is deployed.

d. Remove the rudder from the STANDBY hydraulic system.

e. Remove control cable runs (except for aileron wing cables and the stabilizer cables or chain), input quadrants, feel/trim units, and actuator installations (except for elevator and aileron output quadrants and surface linkages, ground spoiler linkages, and rudder-pedal nosewheel steering and brake linkages).

f. Split the elevator output torque tube and install two FBL actuators on each half (one to each elevator panel). (Retention of the torque tube compliance needs to be studied.)

   (Note: FBL modified dual-tandem actuators were considered for the elevators, ailerons, and rudder. All FBL actuators, both primary and secondary, will have an associated distributed ACE integral to or within 2 ft of the actuator.)

g. Install three FBL actuators on the rudder.

h. Install two FBL actuators on each aileron wing cable quadrant.

   (Note: Both the elevator torque tube/push-rod and the aileron wing cables substantially limit the control bandwidth of these surfaces. This will preclude use of any high-bandpass functions, such as flutter suppression. If experiments requiring such functions are anticipated, the requirement for this capability needs to be specified for the detail design.)

i. Install spoiler FBL actuators (similar to 757 spoiler actuators).

j. Modify the cockpit controllers to provide fixed feel and to install FBL sensor modules. Install three PCE units beneath the cockpit floor. The PCEs will provide the interface between the pilot controllers and the ARINC 629 busses.

k. Modify the stabilizer control to provide FBL control of both the main and autopilot motors. Replace the autopilot motor with the increased-rate, two-speed motor, if not already accomplished.

l. Modify the existing main hydraulic and alternate electric trailing-edge flap motors for FBL control. (In the detailed design, consideration could also be given to providing separate control of each flap section.)

m. Replace the existing leading-edge actuator control module with an FBL control module that provides individual control of each flap or slat.

n. Remove the existing pitot probes, static ports, angle-of-attack (AOA) vanes and total-air-temperature sensor. Install three FBL pitot air data modules, three FBL static air data modules, three FBL AOA air data modules and a total-air-temperature air data module.

o. Remove the existing ADIRU and air data computers. Install an FBL ADIRU and an FBL SAARU.

p. Install three PFCs, three IAUs, three FBL power supply assemblies and two SFCs maintaining at least 6 ft of separation between like units. Space should be allocated for the consolidated ACEs of phase II with the same separation requirements.

(Note: Exceptions to the 6-ft separation requirement will be evaluated on an individual basis.)

q. Install the three FBL ARINC 629 buses, fiber-optic backup lines, and ARINC 629 stubs, maintaining the 6-ft separation between buses and maintaining as much separation between stubs of the different buses as is practical.

r. Install the FBL electrical power wiring maintaining the 6-ft separation between power from the different buses. Where this separation is not practical, the maximum separation practical will be maintained.

7.2.1.2 Phase II TSRV Modifications

The phase II FBL system configuration is shown in figure 3-2. The phase II modifications affect only the ACE/actuator and controller sensor and PCE combinations. The changes are as follows:

a. Remove the FBL ACEs and actuators, including the associated FBL electrical power lines and ARINC 629 stubs. Modify or replace with actuators with optical position sensors. Install phase II actuators and fiber-optic lines to the ACEs for commands and feedback signals.

b. Install the consolidated ACEs. Connect the ACEs to electrical power and DATAC buses and to the fiber-optic lines from the actuators.

c. Remove the pilot controller sensors and PCEs. Install optical pilot controller sensors and connect to the associated consolidated ACE.

d. Replace the thrust lever angle (TLA) resolvers with optical sensors, modify the electronic engine controls (EEC) to interface with the optical sensors and install an optical link between the sensors and the EECs.

(Note: The optical link and the interface at the engines need to be high-temperature (> 200° C) devices.)

e. Replace all ten of the air data modules with units incorporating optical sensing of the respective air data parameters.

7.2.1.3 Phase III TSRV Modifications

The phase III modifications are as follows:

a. Modify or replace the actuators to provide optical control ("T" valve) power in addition to the optical feedback sensors.

b. Modify the fiber-optic cabling to provide adequate optical power to the actuators.

c. Modify the ACEs so that they can provide adequate optical power to the actuators.

7.2.2 Experimental Avionics Simulation and Integration Laboratory Modifications

The Experimental Avionics Simulation and Integration Laboratory (EASILY) facility will require modification to support the FBL flight control system. These modifications will include the reprogramming of the simulation so that the current mechanical flight control system is removed and the FBL system, where each FBL actuator is separately simulated, is added. Interface and test rack(s) to tie the FBL system to the simulation must also be designed and built.

7.2.2.1 Phase I EASILY Modifications

a. Reprogram the simulation such that the current mechanical flight control system is removed and the FBL system, where each FBL ACE or actuator is separately simulated, is added.

b. Design and build interface and test rack(s) to tie the FBL PCEs, IAUs, PFCs, and SFCs to the simulation.

7.2.2.2 Phase II EASILY Modifications

a. Reprogram the simulation so that the FBL ACE is removed from the actuator simulation.

b. Modify the interface and test rack(s) to remove the FBL PCEs and add the optical paths from the simulated pilot controllers to the associated consolidated ACEs.

c. Add the consolidated ACEs optical interfaces with the simulated actuators.

7.2.2.3 Phase III EASILY Modifications

Modify the interface and test rack(s) to incorporate the consolidated ACEs optical power interfaces with the simulated actuators.

7.2.3 Experimental System Modifications

Because of the nature of the ATOPS experiments, it will be necessary to collect an enormous quantity of data. The addition of the FBL control system, with its additional data requirements, may make the present data system obsolete. The addition or modification of the DAS should be considered.

Because of the flight criticality of the FBL flight control system and the integrity it requires of certain sensor signals, the landing gear module and the low-range radio altimeters (LRRA) will need to interface directly with the IAUs.

7.2.3.1 Phase I Experimental System Modifications

Interface the landing gear module, the LRRAs, and the experimental system DATAC directly with the IAUs.

7.2.3.2 Phase II Experimental System Modifications

None identified.

7.2.3.3 Phase III Experimental System Modifications

None identified.

8.0 SCHEDULE

The schedule for the three phases of the fly-by-light (FBL) flight control system is shown in figures 8-1 through 8-4. The major milestones include the availability of funding starting in October, 1990, the availability of fiber-optic components like ARINC 629 bus, transceivers, and analog backup link in November, 1990 and the start of flight test on the NASA Transport Systems Research Vehicle (TSRV) in September, 1992.

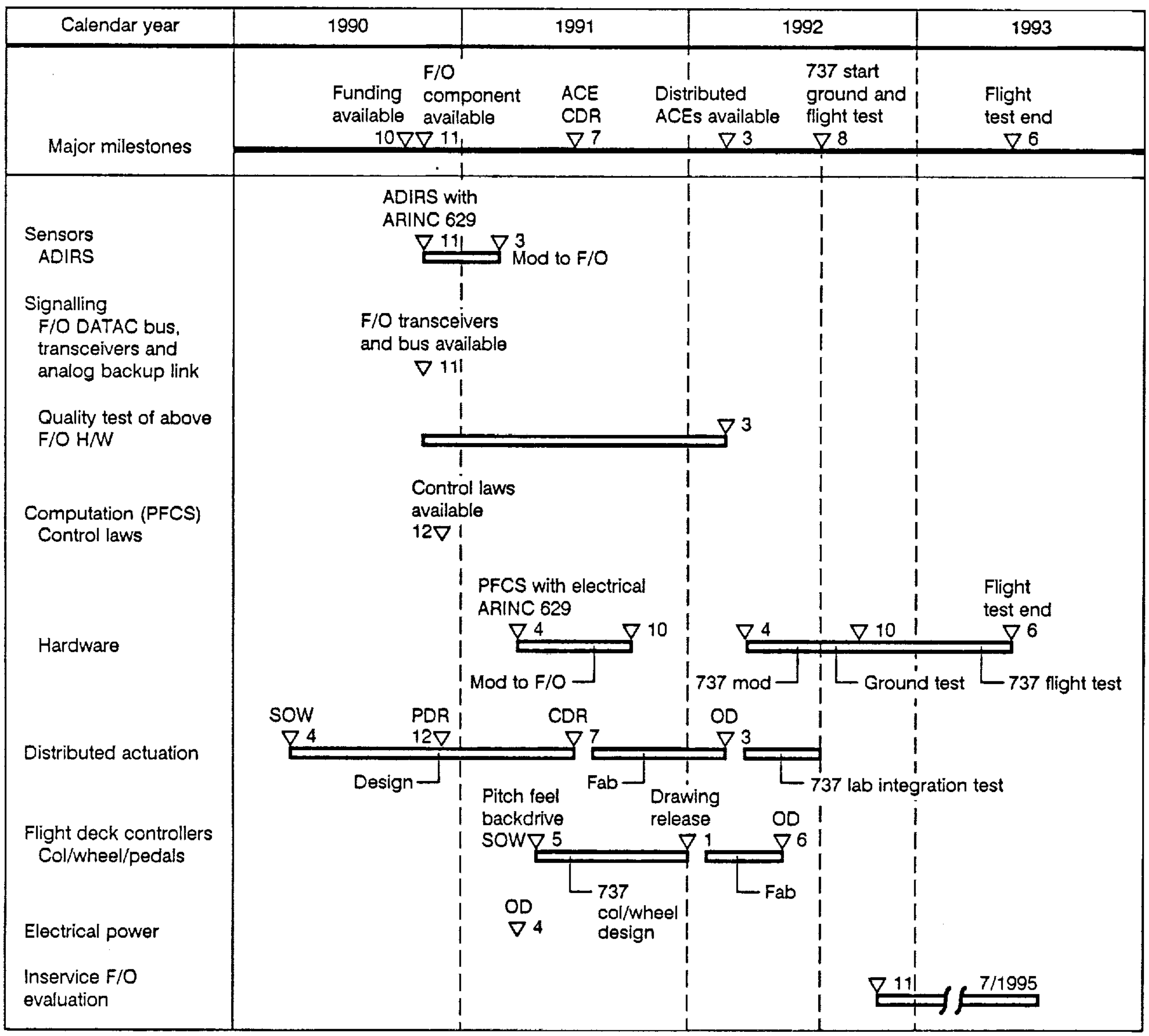

Figure 8-1. Schedule for FBL Control System (Phase I)

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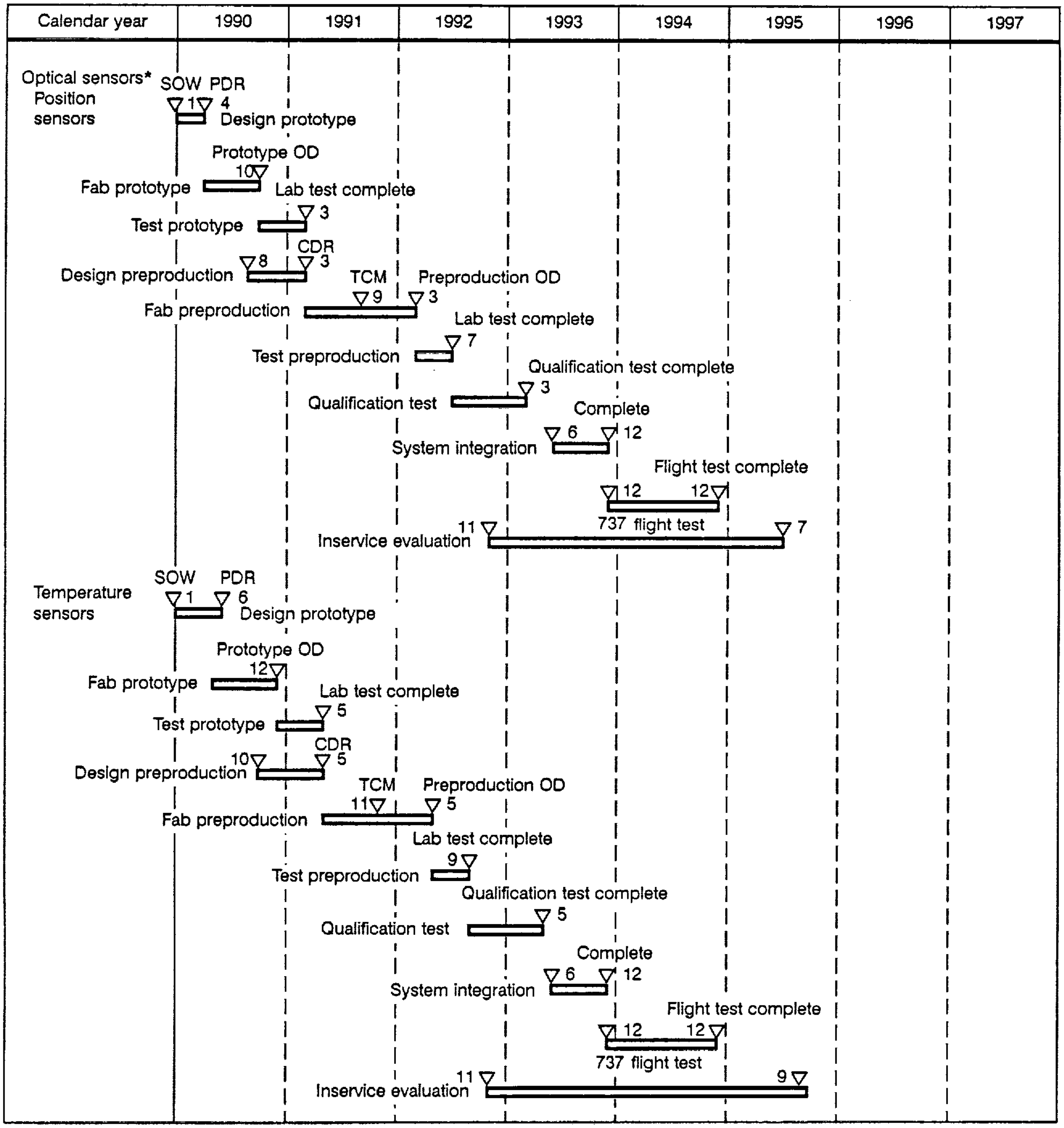

*Refer to the Development Plan for NASA/Boeing coverage.

Figure 8-2. Schedule for FBL Control System (Phase II)

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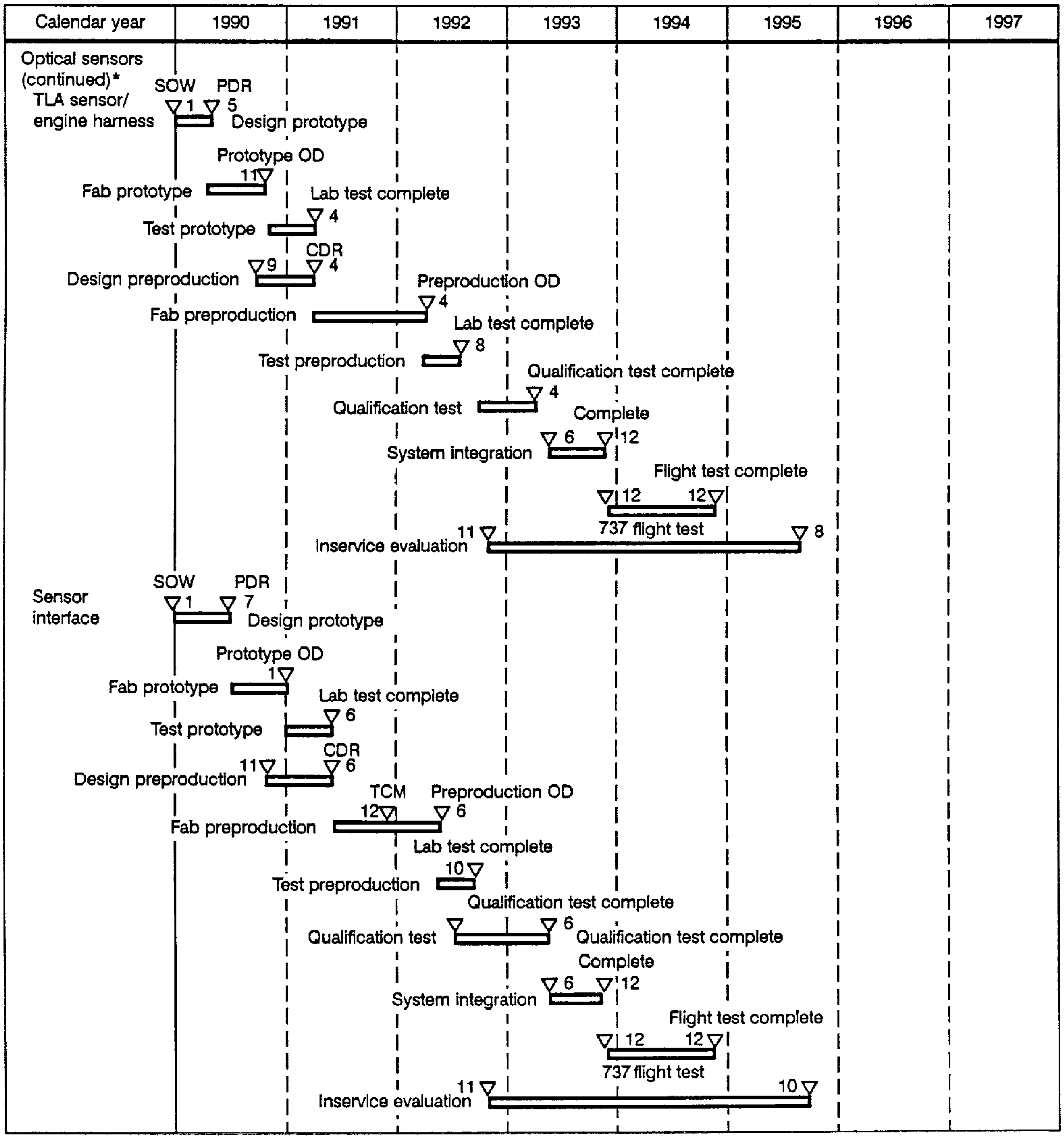
Phase I flight test will be between September, 1992 and June, 1993; phase II flight testing will be conducted between December, 1993 and December, 1994; and phase III flight test will start in December, 1994 and continue through December, 1995. In each phase, the fiber-optic hardware will have gone through qualification testing before the flight test (figs. 8-1 through 8-3).



*Refer to the Development Plan for NASA/Boeing coverage.

Figure 8-2. Schedule for FBL Control System (Phase II) (Continued)

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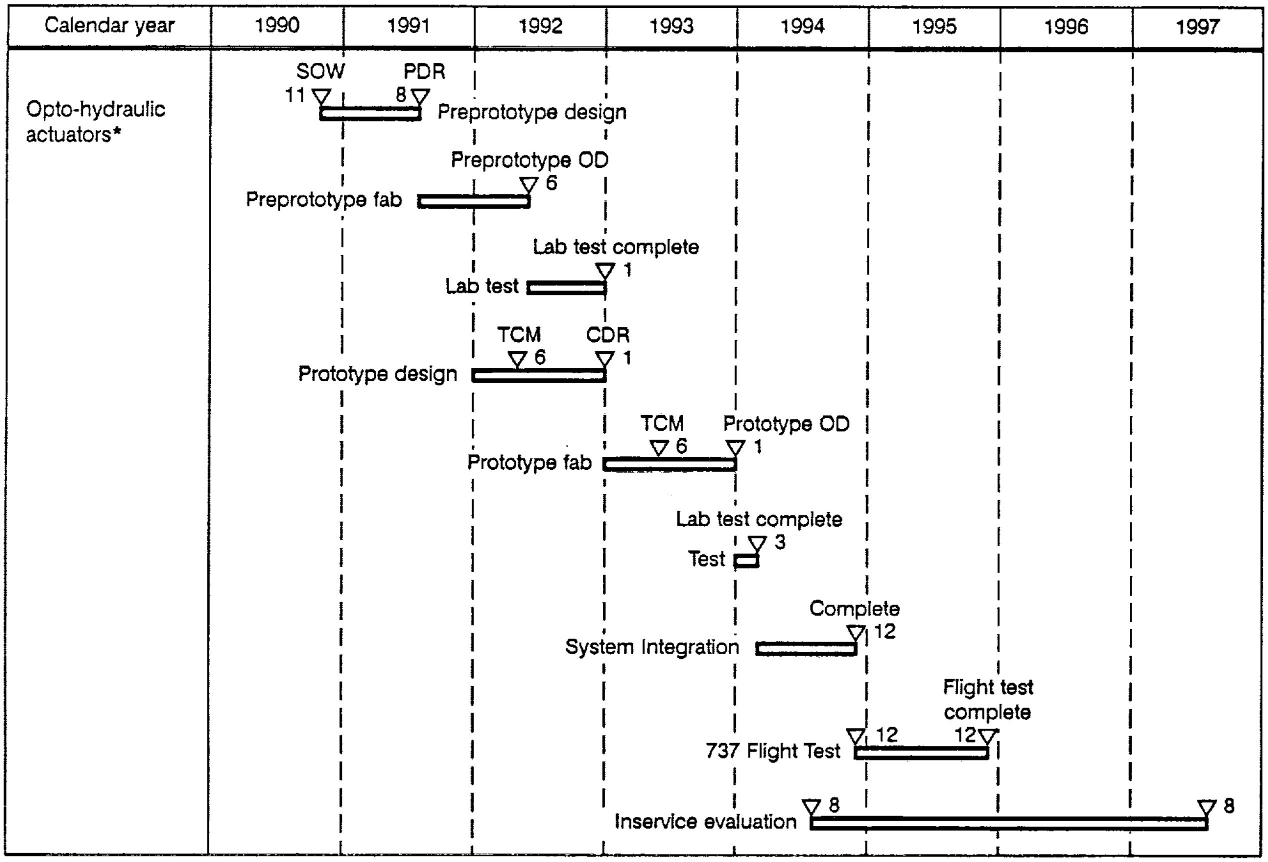
The inservice evaluation of fiber-optic elements will be completed by July, 1995 for phase I components; by October 1995 for phase II components, and by August, 1997 for phase III components. It should be emphasized that this evaluation will be Boeing product-line oriented and will be funded by Boeing resources.



*Refer to the Development Plan for NASA/Boeing coverage

Figure 8-3. Schedule for FBL Control System (Phase III)

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9.0 RESOURCE REQUIREMENTS

The following assumptions and groundrules were used to generate the resource requirements for developing fly-by-light (FBL) technology to production readiness:

a. The identified resource requirements are for the prime contractor and suppliers only.

b. The cost of developing the fly-by-wire (FBW) architecture for the prime contractor internal program is not included.

c. The cost of inservice evaluation of fiber-optic components with the airlines, including cost of prototypes required for the evaluation, is not included.

d. FBL system components, such as distributed actuator control electronics (ACE) and optohydraulic actuators, will be fully funded by NASA.

e. The cost of modifying (i.e., equipment installation) the NASA Transport Systems Research Vehicle (TSRV) to full FBL is not included.

f. It is assumed that the prime contractor can support the NASA FBL program while supporting other internal programs.

g. It is further assumed that suppliers will have adequate manpower and will support the NASA FBL program concurrently with other committed programs.

The resources required by the prime contractor and suppliers to develop, implement, and flight test an FBL flight control system with optical signaling (phase I) on the NASA TSRV by fiscal year are:

FY 1991	FY 1992	FY 1993	FY 1994	Total
\$16M	\$14M	\$8M	\$1M	\$39M

The resources required by the prime contractor and suppliers to develop, implement, and flight test an FBL flight control system with (1) optical position sensors for loop closure using optical links, and (2) optical signaling to actuators using optical control power (i.e., phases II and III) are shown below:

FY 1991	FY 1992	FY 1993	FY 1994	FY 1995	FY 1996	Total
\$20M	\$20M	\$20M	\$21M	\$21M	\$3M	\$105M

The cumulative resource requirements for phases I, II, and III of the FBL flight control system amount to \$144M.

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15. Supplementary Notes

NASA Technical Monitor: Cary Spitzer

16. Abstract

This report documents the results of a four-month, phased effort to develop a Fly-by-Light Technology Development Plan. The technical shortfalls for each phase were identified and a development plan to bridge the technical gap was developed.

The production configuration was defined for a 757-type airplane, but it is suggested that the demonstration flight be conducted on the NASA Transport Systems Research Vehicle. The modifications required and verification and validation issues are delineated in this report. A detailed schedule for the phased introduction of fly-by-light system components has been generated.

It is concluded that a fiber-optics program would contribute significantly toward developing the required state of readiness that will make a fly-by-light control system not only cost effective but reliable without mitigating the weight and high-energy radio frequency related benefits.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Fly-by-Light; Fiber-Optic Shortfalls; Optical Signaling; Optical Sensors; Development Plan	Unclassified-Unlimited

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